

Cognitive Issues Related to Advanced Cockpit Displays:  
Supporting the Transition between Internal and External Guidance

by

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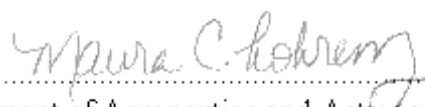
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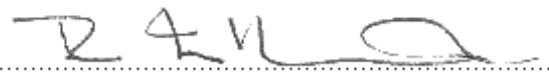
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## **Abstract**

A critical issue in military aviation is the pilot's ability to transition between primarily internal (head-down, instrument-driven) and external (head-up, out of the cockpit) guidance. Experimental cockpit displays were designed and tested for how well they might support this transition phase for military pilots performing time-critical air-to-ground targeting missions such as Forward Air Control and Close Air Support. Twelve subjects performed three sets of experiments using a flight simulator (with simulated heads-up display in the forward field of view) connected to a moving-map display. The experiments were designed to help explain which visual cues in the displays might best help a pilot 1) navigate to a given target area (the "flight guidance" phase of a mission) and 2) search for, find and identify a target (the "target acquisition" phase).

In one experiment, subjects flew a mission using three different versions of a plan-view moving-map display: 1) a detailed, topographic map with high-contrast mission overlays, 2) the map only, and 3) the overlays only. Overall, both flight guidance and target acquisition performance were best and workload was lowest while using the simplest, overlays-only display; performance and workload were equivalent or worse with the combination display, and significantly worse with the map-only display. These results suggest that the simplest possible display, portraying only the necessary information, is optimal. The distraction of display clutter often outweighs the potential benefits of additional information, especially when the display must support a time-critical task such as air-to-ground targeting.

In all experiments, subjects demonstrated an increased reliance on internal cues (such as the moving-map and other flight instrumentation) during flight guidance and shifted their attention to the external view outside their virtual cockpit during target acquisition. If the target had moved from its expected location, subjects continued switching focus between internal and external cues (a process known as navigational checking) to correlate the various sources of information and find the target.

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## **Abbreviations**

2D / 3D	2 dimensional / 3 dimensional
CAS	Close Air Support
CLOS	Clear Line of Sight
CSAR	Combat Search and Rescue
DTED	Digital Terrain Elevation Data
ERF	Ego-centered Reference Frame
FAC	Forward Air Controller
FAC-A	FAC-Airborne (i.e., pilot)
FAC-G	FAC-Ground (i.e., ground soldier)
FEBA	Forward Edge of Battle Area
FOV	Field of View
FFOV	Forward Field of View
FLIR	Forward-Looking Infrared Radar
FLOT	Forward Line of Troops
FS2002	Flight Simulator 2002 (Microsoft)
GIDB	Geospatial Information Data Base
GPS	Global Positioning System
HAT	Height above Terrain (or Threshold or Target)
HSI	Horizontal Situation Indicator
HUD	Head-Up Display
IFR	Instrument Flight Rules
INS	Inertial Navigation System
NIMA	National Imagery and Mapping Agency
NMEA	National Marine Electronics Association
NPFPS	Navy Portable Flight Planning System
NRL	Naval Research Laboratory
NVG	Night Vision Goggles
RMSE	Root Mean Squared Error
SA	Situation Awareness
TAMMAC	Tactical Aircraft Moving Map Capability
TAWS	Terrain Avoidance Warning System
USGS	United States Geological Survey
WRF	World-centered Reference Frame

# **1. Introduction**

## **1.1 Motivation**

A critical issue in military aviation is the pilot's ability to transition between primarily internal (head-down, instrument-driven) and external (head-up, out of the cockpit) guidance. Military pilots report difficulties during this transition phase, particularly during time-critical target acquisition missions such as Close Air Support (CAS) and Forward Air Control (FAC). Parallel issues exist in civilian aviation; for example, during circling Instrument Flight Rules (IFR) approaches, the pilot must transition between internal guidance while flying through clouds and external guidance below the ceiling. The military scenario is complicated by the fact that the target may be mobile and unpredictable, whereas the civilian "target" – the runway – is fixed.

The goal of this thesis is to investigate, test, and compare selected cockpit display techniques to improve this transition between internal and external guidance. Tools to synchronize internal and external information paths are expected to support communication and coordination among mission subjects (e.g., CAS pilots and FAC ground troops; or civilian pilots and air traffic controllers), improving the transition phase and increasing the potential for mission success. Three experiments were performed in an attempt to address these issues. Performance and workload measurements were compared for subjects flying a simulated aircraft while referring to conformal, scene-linked, 3-dimensional (3D) symbology on a head-up display (HUD); the equivalent symbology presented on a head-down, 2D moving-map display; or both. Specific questions to be investigated include the following: 1) Which of the tested display techniques best support the transition between internally dominant and externally dominant guidance? 2) Which display techniques best support flight guidance and target acquisition tasks? 3) How do the different display techniques impact performance and workload?

## **1.2 Cockpit moving-maps in support of air-to-ground missions**

Potter, et al. (2002) describe the importance of clearly defining the goals and scope of a display in terms of the cognitive tasks it is intended to support. To that end, designers should specify the decisions to be made, the cognitive performance objectives to be achieved, and the information

(not just the data) to be conveyed by the display. In other words, it is not only important to specify *what* will be displayed, but *how* best to display the information.

Navy air-to-ground missions require precise flight guidance to and from the target area (ingress, egress) and timely, accurate target acquisition (including searching for, locating, and positively identifying the target). The flight guidance and target acquisition phases are closely interrelated. Errors during flight guidance may result in a failure to acquire the target; conversely, flight guidance itself can be seen as a series of intermediate target acquisitions as the pilot searches for and finds “lead-in” features along the route, confirming that he or she is on the right track (Conejo and Wickens, 1997).

Flight guidance is supported by a map or electronic map display (with a focus on sources of information *inside* the cockpit), while target acquisition relies on up-to-date intelligence information – often communicated by a FAC – and considerable attention and focus on the scene *outside* the cockpit. Thus, the pilot must alternate between primarily internal and primarily external guidance throughout the mission, with the focus on the external “real-world” view commanding more and more attention as the target area approaches. Perhaps more importantly, both phases of the mission (flight guidance and target acquisition) require the pilot to correlate inside (e.g., map) and outside views to ensure mission success.

Many researchers have investigated the ways in which pilots correlate different views or frames of reference. Wickens et al. (1989), Aretz (1991), and others have defined the concept of navigational awareness as a cognitive correlation between an ego-centered reference frame (ERF), established by the pilot’s forward field of view (FFOV), and a world-centered reference frame (WRF), established by a map or electronic map display. They ascertain that a pilot’s inability to correlate these reference frames will result in a lack of navigational awareness, leading to spatial disorientation. Aretz (1991) has identified the cognitive operations required to achieve navigational awareness, including triangulation (in which the ERF must uniquely specify a location in the WRF) and mental rotation (including both circular and forward rotations). This research has shown that circular mental rotation can be aided by presenting the map in a track-up orientation, such that the pilot’s view of the map corresponds with his or her view of the ground

below. ERF-based navigation tasks, such as localization, are best supported by a track-up orientation, while WRF-based tasks, such as pre-mission planning, may be best supported by a north-up orientation. On the other hand, Olmos et al. (1997) has demonstrated that global situation awareness (required for WRF tasks) might be better supported by a track-up map display than a north-up map. Pilots in this study could identify a target's location in the FFOV more quickly with a track-up map than a north-up map, which the authors attributed to a common ERF shared between the FFOV and the rotating map.

Forward mental rotation can be aided by presenting salient geospatial cues (such as target location) in a HUD, such that the pilot's view of the cues is coincident with the view outside. The high speed of ingress during air-to-ground attack missions leaves little time for a pilot to compare features on a map with features on the ground (Pringle et al., 1998). Rendering the map (or geospatial cues) in a way that is most congruent with the pilot's forward field of view should assist the pilot during time-constrained tasks such as target acquisition.

Researchers have identified a potentially dangerous consequence of using HUDs known as attentional tunneling, or attending to the information presented on the HUD at the expense of the view outside the cockpit window (e.g., Foyle et al., 1995; Wickens and Long, 1994 and 1995; Hooey, et al., 2001). This problem can be alleviated by replacing superimposed symbology (in which the symbols are mostly presented at a fixed, specific location on the HUD screen) with scene-linked, conformal symbology (in which the symbols are virtually placed in the outside scene and appear to be part of the environment).

Aretz (1998) conducted an extensive literature review of the advantages and disadvantages associated with various frames of reference with respect to electronic map displays for low altitude, visual flight rules (VFR) helicopter flight. Although the current thesis focuses on fixed-wing aircraft, Aretz's paper is particularly relevant, since many air-to-ground military missions are performed at low altitude and require VFR (or near-VFR) weather conditions for successful target acquisition. Aretz has identified several parameters that should be considered when determining which reference frame is best for any electronic map display, including orientation (e.g., track-up vs. north-up) and viewpoint (e.g., 3D perspective vs. 2D planar), as discussed

previously. For 3D displays, he also compared the egocentric (or immersed) view vs. exocentric view (in which the aircraft itself is included in the field of view). Aretz's review concludes that a rotating, track-up map display results in greater flight guidance accuracy (e.g., Aretz, 1991; Olmos et al., 1997) as well as improved hazard awareness and global situation awareness (e.g., Olmos et al., 1997), compared with a north-up display. The egocentric view results in better local guidance (e.g., Wickens and Prevett, 1995) and may be especially advantageous for very low altitude flights (Hickox and Wickens, 1996), but it results in poorer global Situational Awareness (SA) than the exocentric view (e.g., Wickens, 1999). However, the exocentric view results in less precise judgments along the line of sight and greater ambiguity about object placement, relative to the egocentric view.

In summary, the choice of map display (including frame of reference, geographic scale, and information displayed) depends on the tasks to be accomplished. Based on conclusions from the research cited, this author selected a track-up 2D moving-map display and egocentric 3D display (consisting of conformal, scene-linked, symbology superimposed on the FFOV) for the experiments presented in this thesis.

### **1.3 Overview of thesis organization**

The thesis organization follows the evolution of the project itself. The section following this Introduction is dedicated to several focused interviews that were held with F/A-18 pilots experienced in the use of cockpit moving-map displays. These pilots led the author to investigate methods by which advanced cockpit displays might support the transition between internally dominant and externally dominant tasking during air-to-ground missions, such as CAS and FAC. The interview discussions can be seen as an informal task analysis of these missions, from the perspective of utilizing a map display or HUD.

The third section of the thesis proposes a cognitive process model developed from these interviews and discussions. The model is intended to help visualize how a pilot senses, perceives, integrates and correlates the many – and sometimes disparate – sources of information available to support successful decision-making and ultimate control of the aircraft. The proposed model can be used to identify possible deficiencies in the pilot's decision-making –

particularly during the integration and correlation of multiple sources of information – and to suggest appropriate remedies.

The fourth section presents several hypotheses for improving pilots' correlation of information in support of two primary phases of an air-to-ground mission: flight guidance and target acquisition. Three experiments are proposed to test those hypotheses. Detailed experimental methods and statistical analyses of results are included in this section.

The fifth section summarizes experimental results and presents relevant conclusions. A list of references and four appendices are provided. Appendix A provides the source code for a computer program, developed for this thesis, that links Microsoft Flight Simulator (running on one PC) with a moving-map program running on another PC. Appendix B provides the calculations for the root mean squared error (RMSE) between the actual and planned flight paths and the RMSE between the actual and planned altitudes (measures of flight guidance performance and workload). Appendix C provides plots of experimental results for each subject. Appendix D includes a copy of the consent form completed by each subject prior to participating in the experiments and the debriefing statement provided to each subject following their participation.

## **2. Pilot Interviews**

Three F/A-18 pilots with experience using cockpit moving-map displays were interviewed in October 2001 at the Naval Air Warfare Center in Patuxent River, MD. The purpose of the interviews was to gain insights into how these pilots used the displays to assist them with various missions and to solicit recommendations for improvements to existing displays, based on the pilots' mission requirements. The primary interview topics included 1) general information about the pilot; 2) tactical air missions that are (or could be) supported by a moving-map; 3) how the pilots acquire and maintain SA; and 4) recommendations for new moving-map display functions. Follow-up telephone interviews with two of the pilots were conducted in March 2002 to focus on specific issues raised during the initial interviews, including the degree of flexibility a pilot has in executing air-to-ground missions and a proposed transition phase between "internally dominant" and "externally dominant" guidance in many air-to-ground missions. Table 2-1 presents questions that were used to focus the interview sessions.

### **2.1 General Information**

All three pilots were experienced flying the F/A-18 fighter jet, with 1200, 800, and 700 hours as pilot in command, respectively (table 2-2). Most of their flight time was in the older F/A-18 C/D "Hornet" (C designates a single-seat cockpit, and D designates a dual-seater with both a pilot and navigator). The F/A-18 C/D is equipped with a moving-map system that displays scanned aeronautical charts with pilot-selected overlays of certain mission and intelligence information, such as approximate locations of threats and targets.

Two of the pilots also had limited experience in the newer F/A-18 E/F "Super Hornet" (E has a single seat; F is a dual-seater). The F/A-18 E/F is equipped with newer avionics and cockpit displays, including the Tactical Aircraft Moving Map Capabilities (TAMMAC) system. TAMMAC can display satellite imagery, in addition to scanned charts, along with more advanced mission graphics such as height-above-terrain (HAT) and clear line-of-sight (CLOS) overlays. HAT uses the Digital Terrain Elevation Database (DTED) to generate shaded overlays depicting terrain that is higher than the aircraft's current altitude; CLOS uses DTED to highlight regions that are obscured from the pilot's view due to intervening terrain. A Terrain Avoidance Warning System (TAWS) will also be incorporated into a future version of TAMMAC.

Table 2-1. List of questions used to conduct focused interviews with F/A-18 pilots.

<b>General Information</b>
<ul style="list-style-type: none"> <li>Name, rank, contact information</li> <li>How many hours do you have as Pilot in Command (broken out by aircraft platform)?</li> <li>With which (if any) cockpit moving-map system(s) do you typically / currently fly?</li> </ul>
<b>Tactical Missions Flown</b>
<ul style="list-style-type: none"> <li>With which tactical missions do you have experience?</li> <li>If you could think of a particular mission scenario, from the point of view of using the map, what would be one of the most challenging scenarios, and how would you use the map?</li> <li>What features or functions were missing from the moving-map that you could have used in this situation?</li> </ul>
<b>Situation Awareness (SA)</b>
<ul style="list-style-type: none"> <li>Specifically what does SA mean to you?</li> <li>How do you acquire SA (step by step)?</li> <li>How do you use the current moving-map display to support your development of SA?</li> <li>Is there anything that could be done to the moving map to further enhance your SA?</li> <li>What features or functions are missing from the current moving-map that you wish you had, for improved SA?</li> </ul>
<b>Advanced Moving-Map Display Recommendations</b>
<ul style="list-style-type: none"> <li>The TAMMAC map display offers several new functions (e.g., HAT and CLOS overlays). Are all these new functions useful to you?</li> <li>What other functions would you like to see incorporated into a moving-map display?</li> <li>Does your current moving map provide these functions?</li> <li>If so, how could they be improved?</li> <li>If not, how would you implement them?</li> </ul>
<b>Pilot Flexibility</b>
<ul style="list-style-type: none"> <li>How does a pilots' level of flexibility (e.g., in ingress / egress routes) impact their ability to accomplish their mission?</li> <li>What, if anything, limits your flexibility (in terms of both internal and external guidance)?</li> <li>Why is your flexibility limited (internal / external guidance)?</li> <li>How could this flexibility be improved (internal / external guidance)?</li> <li>If a target is not located where you expected (e.g., if you had bad intelligence information), what do you do next?</li> </ul>
<b>Transition Phase (Internal ↔ External Guidance)</b>
<ul style="list-style-type: none"> <li>There seems to be a transition phase in many air-to-ground missions from "internally dominant guidance" (i.e., relying primarily on cockpit instrumentation, including the map display, for flight guidance) to "externally dominant guidance" (i.e., relying primarily on the outside world view for target acquisition) as you approach a target or region of interest. Does this make sense?</li> <li>If so, can you expand on this idea?</li> <li>How could the internal portion of your flight guidance assistance be improved (e.g., map display, other instruments)?</li> </ul>



Over the next several years, the TAMMAC program office plans to incorporate additional advanced functions that will rely on the implementation of a vector-based map database. Some of these new functions include the ability to selectively add or remove features from the moving-map, query the map for more detailed information, and allow text to remain upright as a track-up map spins (Williams, 1998; Ruffner and Trenchard, 1998).

*Table 2-2. Military flight experience of interviewed pilots.*

Pilot #	Flight hours				Notes
	F/A-18 C/D	F/A-18 E/F	Other A/C	Total PIC	
<b>1</b>	1200	50	500	1750	TAMMAC Project Officer
<b>2</b>	800	10	590	1400	24 combat missions (some as flight lead) during Operation Desert Storm
<b>3</b>	700	0	3800	4500	MD; flew in Vietnam and Desert Storm (not as flight lead); tested NVG and MM displays

All three pilots had additional experience flying other aircraft without a moving-map display (500, 590, and 3800 hours, respectively). At the time of these interviews, the first pilot was the F/A-18 project officer for the TAMMAC program, so he was very familiar with both existing and planned moving-map capabilities for this aircraft. The second pilot had extensive combat flight experience, having completed 24 combat missions (some as a flight lead) during Operation Desert Storm in the early 1990's. The third pilot (who is also a medical doctor) had flown during both Vietnam and Desert Storm, and had over 4500 total flight hours in the military. He had considerable experience testing night vision goggles (NVG) and moving-map displays during training and test flights.

## **2.2 Air-to-Ground Missions**

The three pilots identified several missions for which they would use (or had used) a moving-map display, including Forward Air Control (FAC), Close Air Support (CAS), Combat Search and Rescue (CSAR), Deep Strike, and air-to-ground targeting in which the target is stationary (e.g., a building) or moving (e.g., a tank).

The second pilot discussed some of the differences among three F/A-18 air-to-ground missions:

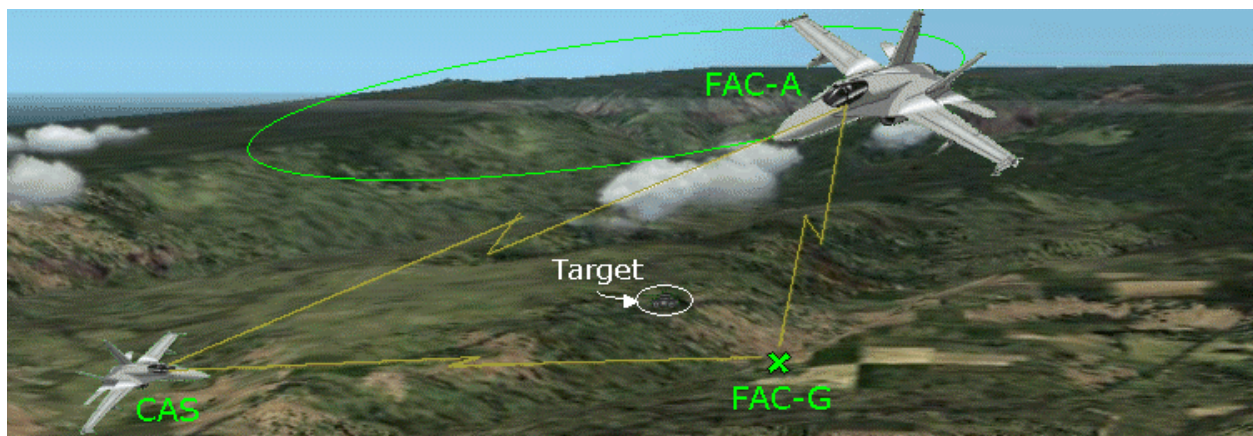
“With CAS, you circle overhead as the FAC talks you through the situation. [In this mission] our friendly forces and enemy forces are both right there. We would have established airspace superiority, so we own the airspace.

“CSAR is a lot like CAS, but there can be more threats. We have a route, like in deep air strike. We need to keep an eye on the rescue helicopter [which flies at] 100 kts max. The “rescort” [F/A-18 rescue escort] job is to provide air cover for the helicopter and [must be able to] visualize the route. The guy to be rescued is sending secure GPS coordinates [to the CSAR].

“Deep Strike or Deep Air Support occurs in the first days of war. We’re hitting the enemy, so there are no friendly forces. We’re taking out a factory, etc., and may not have established any superiority. That [means there is] time pressure. I need to know if that’s an enemy tank without a doubt. On Deep Strike, ... there is a lot of pressure and stress. If I look around and the target’s not there, I will high tail it out of there.”

Despite the danger of Deep Strike, pilots identified the FAC / CAS mission as one of the most difficult air-to-ground missions, because of the close proximity of friendly and enemy troops, the need for close communication between FAC and CAS, and the CAS’ need to correlate numerous sources of information. The pilots also stated that the FAC / CAS mission could specifically benefit from a well-designed cockpit map display. The first pilot described it this way:

“One of the hardest things to do effectively is CAS for friendly troops, but that [mission] is **not** going away in modern warfare. We can have all kinds of smart weapons, and shoot things off ships with GPS guidance, but the guys on the ground are still the ones who will be very dynamically involved and needing very flexible support. That’s where moving-maps [are important], with the ability to cue the pilots in terms of, ‘What is the terrain? Where is the FAC? What do things look like? Where is the target?’ That’s when it gets really important. We’re talking the new war on terrorism – very mobile, very tiny, very difficult. That kind of stuff will be next to impossible unless you have near-instantaneous data.”



*Figure 1-1. Illustration of a sample FAC / CAS mission.*

Table 2-3. Summary of tasks comprising a typical FAC-G / CAS mission.

<b>Goal</b>	CAS must locate and eliminate threat(s) based on recently transmitted information from FAC and other intelligence sources.
<b>Description</b>	Orienting (with waypoints) to unknown / unfamiliar area under dynamic conditions. Terrain avoidance in low visibility. Guys on ground need flexible, dynamic support. Moving-maps cue pilots: what is terrain, where is FAC, what do things look like?
<b>Steps to accomplish goal (while flying to area of interest)</b>	<ol style="list-style-type: none"> <li>1) Receive new intell data (e.g., target is a green truck, moving west from a specified location in a valley).</li> <li>2) Study reconnaissance photo or other imagery uplinked from the FAC or other sources.</li> <li>3) Study map: identify terrain shading / contours and easily identifiable, high-contrast lead-in features (e.g., river, road).</li> <li>4) Look outside, find the same feature(s).</li> <li>5) Correlate outside view with map, pictures.</li> <li>6) Orient self in view.</li> <li>7) Slew map or imagery to general target area.</li> <li>8) Correlate last known target location with surrounding map features.</li> <li>9) Develop mental model of where to expect target, once aircraft is within visual range.</li> <li>10) Rule out improbable routes (not through mountains to north, not through swamp to south).</li> <li>11) Refine probable route. E.g., valley / river bed / road goes west, Intell said target is heading west → search west.</li> <li>12) Orient aircraft with target's probable route.</li> <li>13) Follow cues from aircraft's current position to target. E.g., find the bend in the river, then find the peak in the mountain, then find a tan field halfway between the bend and the peak, then go to the south side of the field, then find a building. On the west side of the building find a truck, fly close enough to verify the truck is green, lock onto target.</li> <li>14) Repeat any of steps 1-13, as needed.</li> </ol>
<b>Information sources / map functions desired</b>	<ul style="list-style-type: none"> <li>* Real-time intelligence information.</li> <li>* Accurate, concise, readily interpretable map data at several scales (e.g., 1:50k, 1:250k).</li> <li>* Easily identifiable geographic features on the map for visual cueing (e.g., roads, bridges, railroads, etc.).</li> <li>* Accurate terrain elevation data.</li> <li>* Real-time or very recent (depending on the speed of the target, if moving) satellite imagery or reconnaissance photo presented in 2D plan view, 3D view, or 360 deg inclinable view.</li> </ul>
<b>Problems with current methods / tools</b>	<ul style="list-style-type: none"> <li>* Hard to pinpoint FAC location when friendlies and enemies are close together (F/A-18 can cover 1/2 mi in 2 sec).</li> <li>* Need 1:50k map scale for details, but it's hard to see much on a 4.5" screen. Pilots usually still use a paper map to see the whole area at required detail.</li> <li>* Would help to have better slew capability: enter FAC or target location, tell computer to "go to this grid."</li> <li>* Would help to be able to quickly switch back and forth between close-up view of grid and further-out view of surrounding area.</li> <li>* Map features should be easier to identify (e.g., bridge vs. tunnel).</li> <li>* Problems with a picture of the target from the ground (wrong perspective: more confusing than a smaller-scale, plan view, satellite image of target in its surroundings).</li> </ul>

According to the second pilot interviewed, a given FAC / CAS mission might be supported by one or more FAC-Ground (FAC-G) troops, FAC-Airborne (FAC-A) pilots, or a combination of both, who are in radio contact with another pilot providing CAS (figure 1-1). Perhaps a FAC-G sees an enemy tank rapidly encroaching on his or her position and radios instructions to guide the CAS pilot into the area and fire on the tank. To successfully accomplish the mission, the CAS pilot must correlate information from several sources, including the FAC-G's instructions (which are brief and cryptic), the view outside the cockpit, Forward Looking Infrared Radar (FLIR) imagery (if available), and the moving-map. Table 2-3 summarizes the tasks that make up a typical FAC / CAS mission, information needed to support this mission, and several problems with current displays, based on a combination of discussions with the interviewed pilots.

## 2.3 Situation Awareness (SA)

Endsley (1995) has formulated a widely accepted, three-tiered definition of SA as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status into the near future." A pilot must obtain different elements of awareness (e.g., hazard awareness, navigational awareness, automation mode awareness) in order to achieve SA under different circumstances (Endsley, et al., 1998). Therefore, understanding how a FAC / CAS pilot acquires SA should be an important step toward identifying the appropriate tools to help that pilot perform a FAC / CAS mission more effectively.

All three pilots interviewed for this thesis emphasized the importance of acquiring and maintaining SA during flight, but particularly during the dynamic and mentally taxing military air-to-ground missions. The second pilot gave his definition of SA and explained how he acquires and maintains it:

**"Overall, SA is knowing where you are, what's going on around you, and projecting into the future** what needs to happen, what you need to do with the airplane, and what potential problems are developing. SA is where it's at; especially for an F/A-18 pilot and especially for a flight lead.

**"Let's start with why SA breaks down. For me, SA breaks down when something distracts me,** something that wasn't expected, ... something weird. For example, if communications are breaking down, because someone isn't on the frequency they're supposed to be on. With a distraction, you end up fixating on that problem, trying to solve that problem, at the expense of all the other things that are going on that you need to be aware of, such as: Where's my wingman?"

Is he flying in proper formation? Where is the tanker? Who's on the radar display? Are we in the right piece of sky? What's coming up next?"

"Basically, [I regain SA] by solving that problem or ignoring that problem and figuring out if that thing that's distracting you is really that big of a deal. If it is a big deal, you have to focus on it. You can't keep scanning for other things; you have to fix it. It's tough. SA is what separates an F/A-18 pilot from anything else. Especially if you're an F/A-18 flight lead, you have to have 'God-like SA'. That's what we always say! You have to know what's going on all around you."

Numerous aspects of SA are required for the FAC / CAS mission, as the third pilot described:

"There's navigational SA, tactical SA, communication SA, all of it together is knowing what your mission is, where you are, what your job is, where the bad guys are, what's happening behind you, what your weather is doing, the whole thing. **The [important] thing to me about SA is** not to get behind the aircraft but **to stay ahead of the aircraft**. If you get behind at any point, your SA is also behind."

The third pilot emphasized the **importance of communication and trust** in establishing and maintaining shared SA in missions that involve more than one aircraft:

"Your SA is somewhat divided between yourself and your lead [aircraft], and your tasking [is divided] between your lead and your wingman. A lot of a wingman's SA is derived from the lead. [The wingman must] assume the lead knows where he is ... If your lead flies into a mountain, you should be a heartbeat right behind him!

"Talking [with your lead] is essential: paying attention to where you are, knowing when to get your weapon system set up, knowing what kind of maneuver you're going to conduct. When you're not talking to each other, SA becomes more difficult. Even getting four people to agree on what the mission is [is difficult]!"

**Managing inevitable change** in a mission scenario is crucial to maintaining SA (third pilot):

"I don't think I've ever flown a flight that went exactly as it was briefed, because change is a part of the [mission]. I've been on a lot of mishap boards; for most of [them], change has been an integral part of the mishap. This [includes] changes in the flight crew or schedule or launch time or target, from the time you sit down and start planning until the time you're out on the mission, any change in there can effect things. You have to understand what a change means and then how to [manage] that change ... that's all a part of SA."

The cockpit tools that can help a military pilot acquire SA are mission dependent, as the first pilot explained:

"It depends on what the mission is, and what I'm doing. If I'm doing air-to-ground, then I'm worried about the ground. If I'm flying air-to-air, I'm just worried about where I am

geographically. Sometimes, [for air-to-air] I just need a little box on a blank screen. But the rest of the time, I will have done some preflight planning, so I'm going to have a [preconceived] picture of where everything is. Depending on how accurate a study I was able to do, I will want to visually correlate where I am into my big geographic picture. The first thing I'll do is look around and, if I can, see where I am. I'll correlate that with my mentally derived picture of what things 'should' look like, based on my preflight study. Then, I'll 'come inside' to look at the map and determine what I could see outside that I can correlate to my map. Then, I can start using the map to judge distances to features. How I perceive distance will vary, based on my altitude and depression angle. If I'm really high, I'm going to look like I'm close to everything. If I'm flying at night, NVG can really destroy distance perception, because I can see stuff so far away."

## **2.4 Advanced Moving-Map Display Recommendations**

Current military moving-map systems can display scanned aeronautical charts, satellite imagery, reconnaissance photographs, and potentially anything that can be displayed as a digital, raster image. Future moving-map systems will also be able to display features from vector-based geospatial databases, such that individual map features can be manipulated, allowing the display to be customized (Lohrenz, et al., 1997). Given the vast amount of information available, cockpit map display designers must take care not to present too much, resulting in an overly cluttered display. In addition, designers must weigh the benefits of cartographic flexibility (i.e., the ability of pilots to customize their own displays) against pilot workload. A good cockpit moving-map system conveys critical information concerning navigation, threats, and targets in a manner that is easily interpretable under often-stressful conditions. The pilots who were interviewed for this thesis shed some light on which geospatial information is most critical for air-to-ground targeting missions such as FAC / CAS. This section summarizes their responses.

### **2.4.1 Geospatial features of interest**

Typically, the pilots use a moving-map to help them find geographic and stationary threats (e.g., rising terrain, power lines, towers, etc.) and navigational "handles" to use as lead-in features to a target area, if the map is of a large enough scale. The second pilot gave some examples:

"In the F/A-18, the primary information I need from the map is a 'God's eye view' [i.e., 2D plan view] of what's going on: boundaries of areas I'm trying to stay inside of, routes – low level, strike route, 'yellow brick road' – and the sequence of points I'm trying to fly. Other information currently displayed on the digital map, like terrain and airfields, really is not required for the F/A-18. The digital map is good for correlating critical items (routes and waypoints) with what the pilot is seeing outside. For example, while following the yellow-brick road, if you know the next waypoint is supposed to be over an airfield and, in fact, you can see the airfield symbol on the map under the waypoint symbol, it gives you a 'warm and fuzzy' [feeling that you're on the right track]."

The third pilot explained how he has tried to correlate the information on the map with his view outside the window:

“For example, if you see a power line going across the map, you know darned well you’re not going to see the power lines in real life. But, you might be able to see the pylons on top of a mountain, if you have enough contrast [e.g., dark pylons against a light sky], so you would look for the pylons.”

When asked what features or functions he would like on the moving-map display to better support FAC / CAS missions specifically, the second pilot discussed the need for more descriptive, mission-specific symbology:

“In a FAC type mission, we have CP (control points) where the CAS airplanes are hanging out, IP (initial points) to fly through to get you on the right attack axis, and targets. We can have multiple CPs and IPs. When we’re making charts and putting a plan together, we have different symbols for those different points, but you can’t do that on the HSI [Horizontal Situation Indicator display], which is not good. They’re all the same “waypoint” symbol, which is a little circle. [Drawing on our charts,] we use a circle for a CP, a square for the IP, and a triangle for the target. It would be great if you could code those on the moving-map.”

“The FAC-A needs the Forward Edge of Battle Area (FEBA) and the Forward Line of Troops (FLOT). Those different boundaries would be good to display in different colors. Right now, ... it’s all green and it’s just a line. It would be great if ... the squadron could standardize it ... and decide to always put the FEBA in black, always put the FLOT in green, CPs will be circles, IPs will be squares, targets will be triangles, and it would be standardized. Then you could just look at your map and it would make a lot more sense. This, for me personally, would be huge. Use colors and different symbols; go through the critical things that we use, which are waypoints, airfields, and maybe terrain, but no roads or names of all the cities. There’s too much stuff on the map, and [the screen] is too small.”

The second pilot discussed ways in which several aircraft flying in formation might use the moving-map display. When asked how important it would be for them all to be viewing the same information on the map display, he answered:

“It can be [important]. Or it can be that one guy is responsible for one thing, another guy responsible for another thing. It depends on the situation and on the flight lead; the top gun will decide. There is a division of airplanes doing different things, looking at different pictures. I might say, ‘Wingman, while we’re on this cross-country flight, I want you looking at emergency airfields.’ Then if one of us has a problem, he’s ready and immediately can say, ‘Hey, the nearest airfield is 170 deg at 30 miles’. But there are also missions where everyone needs to be looking at the same [map]. It must be standardized somehow, but still be flexible. For example, it would be nice if the flight lead could tell the map to show him exactly what his wingman is looking at.”

#### 2.4.2. Correlating ground and air perspectives

The first pilot talked about the difficulties of correlating the FAC-G view from the ground with the CAS view from the air:

“This is a big problem – there are very different perspectives from the ground vs. the aircraft. A 50 ft rise on the ground is a hill; in the air, it’s nothing! A FAC could data-link his position [to the CAS, who could] then slew over and elevate [the display] to see where the threat is that [the FAC is] talking about.”

This problem with conflicting perspectives must be addressed before reconnaissance photographs (which can be displayed on the moving-map display) are useful in a FAC-G / CAS mission. The first pilot described having to mentally rotate an image taken from one perspective on the ground to match his own perspective from the air:

“To provide me with a picture in the cockpit, [reconnaissance troops] went out and took a picture of the target from the ground. It was a very clear photo, so I knew what I was looking for. Here’s the problem: I am not coming in from the same perspective! [The picture was] taken from the ground, while I’m going to see it from overhead. Now I have to correlate my ingress direction ... with whatever direction this photo was taken. They gave me a picture of the truck from the side, but I’m flying in from the nose of the truck. It looks absolutely nothing like the picture, so the picture actually confuses me at this point, because now I have to correlate in my mind what that truck would look like if I were coming from it straight on.”

However, the same pilot predicted that reconnaissance photographs taken by a FAC-A pilot might be very useful to a CAS pilot, assuming the FAC-A knew from which direction the CAS would be flying. In this scenario, the photographs would serve as a visual link to facilitate communications between the two partners:

“When you get into FAC[-A] and CAS, then [a picture] is important. What’s important to me is where my people on the ground are – and can I correlate that with my mental image of the whole battlefield. Pictures taken by the FAC[-A] and linked to me would be excellent, in that respect. ... Pictures taken from his perspective I can kind of correlate [to my view]: he says he’s here; that’s the view; that will put him about here; OK, that looks right to me.”

#### 2.4.3. Timeliness, accuracy and trust

The first pilot discussed the importance of real-time imagery or photographs in a dynamic targeting scenario, especially when enemy troops are located very close to friendly troops, as in the FAC / CAS mission. If the picture is too old, it becomes useless:



“As a FAC-A, it’s hard to find the friendlies and correlate them to the bad-guys when they’re only ½ mile apart, since I can cover ½ mile in about 2 sec! You’re just zipping by going, wow – who’s who? If I’m going to bomb a bunker, [that’s not a problem because] the bunker’s not going to move. But if I’m talking about vehicles, scud-launchers, how do you find and kill mobile targets? That’s very difficult to do because it’s very dynamic, and **if the information is more than 20-30 minutes old, it’s probably wrong.**”

Trust – or a lack thereof – in the pilot’s various sources of information was a recurring issue discussed in these interviews. If the accuracy and timeliness of the information being provided (e.g., by a moving-map display) cannot be trusted, then the display is of limited use. If the pilot trusts the information, and the information is, in fact, correct, then the display can be of considerable use in making critical decisions. However, if the pilot trusts the information, but the information is actually wrong, then the display can contribute to potentially fatal errors. For example, pilots have been taught not to rely solely on maps (paper or digital) for terrain avoidance, as the first pilot discussed:

“There have been several cases of Hornets flying into mountains because they relied on the INS [Inertial Navigation System] map data when, in fact, there are a lot of ways to get that wrong. Aircrews are very hesitant to use the map for any kind of ‘no-kidding’ terrain avoidance. But, as we graduate into GPS-aided positioning, then I think that will start coming about. ... If you align the INS at the wrong spot, it’s going to send you to the wrong spot. You can align [the GPS] wrong too, but once you get up it will correct itself. Unfortunately, many folks are coming from a background without a GPS-aided jet to rely on; they haven’t really started briefing or training folks to use GPS for any kind of terrain avoidance. I don’t know when that will happen.”

Another issue related to trust was mission urgency. If a mission is critical and urgent, the pilot might be willing to take more risks by trusting the information provided, illustrated in the following account by the first pilot:

“A FAC[-G] positioned in a valley ... wanted to [shoot] a couple of tanks because they were rolling in on his position. He was calling for air support, but it was an overcast, really bad day. The weather was bad enough that ... normal patrols weren’t up. So, the Marines launched with a section of F/A-18s. ... There weren’t any air controllers in the area. The [F/A-18 pilots] had the waypoints, so they looked [at the map], saw where the FAC was in the valley, and just oriented themselves off [the map], let down through the clouds and were able to prosecute an attack on the tanks. So there was a situation where these guys are – despite the fact that they probably shouldn’t be – relying on the map for all their SA and to orient them into the target area. That’s probably a worst-case scenario: close-air support, where you don’t know where people are, or the kind of help they are going to need. You’re launching, but you haven’t been able to do an effective target area study, so you don’t really know where you’re going. That’s about as bad as it gets, where now everything that you’re going to accomplish you’re going to do based on information that’s available in the cockpit. It obviously has to be **concise, readily interpretable, and accurate**, so you can accomplish the mission.”

## 2.5 Pilot Flexibility

This author theorizes that the level of flexibility a pilot has (or believes he or she has) in executing a mission will greatly influence how much (and what) information should be displayed to the pilot. A mission in which the pilot has less flexibility (e.g., if the pilot cannot deviate from a predetermined flight path) would seem to require less assistance than a mission in which the pilot has more flexibility in determining ingress, targeting, and egress maneuvers. A pilot's flexibility on any given mission is closely tied to his or her perceived threat level, as the first pilot interviewed for this thesis explained:

“[My missions are] fairly scripted, depending on the threat level. With a higher threat, I am less flexible, less likely to deviate. A lower threat level means more flexibility. A strike mission is very scripted; FAC/CAS is more flexible. SCAR [Strike Coordination and Armed Reconnaissance] is the most flexible: the aircraft has an assigned area of responsibility, or kill box (10x10 or 20x20 miles) to look for targets. The pilot will call others for support if he finds a target.”

When a pilot arrives at a target area, the target is not always where it was expected to be. There are numerous possible reasons for the problem:

- The target may have moved;
- The target may not be visible to the pilot;
- The pilot may have made an error during ingress to the target area;
- The pilot's ingress was correct, but the pilot may be searching in the wrong place; or
- The pilot's intelligence information may have been wrong.

The pilot's perceived threat level, mission flexibility, confidence in his or her sources of information, and confidence in his or her own performance all dictate how the pilot would handle this situation. The first pilot related his own experience:

“My immediate response is usually, ‘I’m wrong. I need to fix this’. Or, the target moved. I need to go back and compare my mental notes with what I saw [i.e., mentally tracing the route again, from waypoint to waypoint]: the field was right, the barn was right, the map looks right. I need to validate my environment before talking to my FAC again.

“If the threat is low, I’ll stay overhead. With a high threat, I might leave and go elsewhere. If I expect to get shot at, I’ll go away. I might abandon that search and start over again with a new set of references. Although if I am a bomb dropper, I’ll rarely start over.

As military capabilities evolve and threats change on the global scene, pilots must be flexible and adapt old strategies to meet new challenges. The first pilot recalled:

“Folks who flew in the [first] Gulf War [say] it started one way and ended up a completely different way. Tactics change; you meet the environment and a lot of things that previously had been held as paradigms turned out to be wrong. Like going in low. We lost quite a few aircraft [in the beginning] because of outdated tactics. Pilots were trained ... to go in low, thinking that would work, since it always had in the past. Aircraft were getting shot down right and left going in low. So everyone turned around and went in high, and that worked fine. It just depends on being able to adapt to the threat environment. But you learn fast! You can’t train to any one particular threat scenario, because you don’t know what you’re going to face next.”

## **2.6 Supporting the Transition Between Internal and External Guidance**

A recurring theme throughout these interviews was a need for the pilot to alternate between internal cues (the map and other cockpit instruments) and external cues (the world outside). This process has been described by other researchers as *navigational checking* (Wickens, et al., 1994; Schreiber, et al., 1996), in which the pilot compares characteristics of the map with characteristics in the FFOV to determine whether or not the two are congruent (Aretz, 1991). Navigational checking may not require any other action if the pilot determines that the flight is still progressing along the correct path, but the process nevertheless continues throughout the entire flight (Conejo and Wickens, 1997).

One of the topics of this thesis is investigating how this transition between internal and external guidance might change as the pilot nears a target area, and how a given display design might support this transition between the flight guidance (mostly internal) and target acquisition (mostly external) phases of a military air-to-ground mission. This topic was discussed with two of the F/A-18 pilots.

The second pilot described looking for “funneling features” on the ground to cue him into the target area. These could include one or more linear “hand-rail” features, such as a road or river, or a series of “attack points” that lead to the area of interest. The pilot described studying reconnaissance photographs of the target area (if available) and trying to correlate that information with what he saw outside or on his FLIR. Correlating the outside view with a picture can be very difficult, as described earlier, depending on the orientation and perspective of the target in the picture, the time of day the picture was taken, etc.:

“You study the pictures carefully and look at the maps, but the area can look completely different from what you thought. Vegetation, especially, can be a different color. Reconnaissance photos are usually in black and white, which provides better detail; FLIR

is monochromatic [green]. The good [CAS] guys can orient themselves to the map or picture, with [varying] daytime and shadows. [It would help] if you could process a reconnaissance photo to show how the area would look at this time of day and this time of year, [since] the photo could be a year old or a day old.”

The first pilot talked about the hazard of relying too heavily on preconceived ideas about what the target or target area should look like:

“I might have some prejudice from past experience: I’ve been here, I know this area, I have a mental image of this experience. What [the FACs] are describing may match what’s in your head and you don’t think you need to validate it. This is dangerous. [On the other hand,] if you have no idea what they’re talking about, you’ll keep digging until you’re comfortable. If you have prejudice, you expect something based on what you’ve heard – like ‘high terrain’ – but he may be saying a hill, and you’re expecting a mountain.”

This pilot went on to say that good training methods should help alleviate this problem, by teaching FAC and CAS troops how to communicate more effectively with each other. The primary responsibility for good communication in this case lies with the FAC, who must describe his or her surroundings (and specifically, describe the target within the context of its surroundings) in a way in which the CAS can readily interpret.

The second pilot described how a FAC-A pilot and CAS pilot might use a high-contrast ground feature (visible to them both) as a common waypoint and unit of measure. For example, they might agree on the length of a nearby runway as 1 unit of measure. Then, the FAC-A could instruct the CAS on where to fly:

“While the CAS is circling, the FAC-A says, ‘There is a river running N-S. OK, see that bridge crossing the river? Now follow that road east for 3 units’ [i.e., 3 runway lengths]. It’s hard to refer to some [ambiguous] features, like a big field. The FAC-A has a map of the target area, and he’s talking to [FAC-G] guys on the ground; he flies into the target area and looks at the battlefield for a while. The guys on the ground give him a detailed brief, discussing the situation. When the [CAS] aircraft shows up, [things get] very time-critical. They don’t bother referring to their maps [any more] – it’s too time critical.

In this case, the FAC-A was already in the target area, but he still alternated between inside cues (the map) and outside views (the ground) until he understood how best to instruct the CAS pilot when the time came. The final transition occurred when the CAS pilot came into view, and both pilots’ focused on the scene outside. The second pilot suggested that highlighting important

lead-in features and other cues (but not necessarily the target itself) would help improve these transitions between inside and outside:

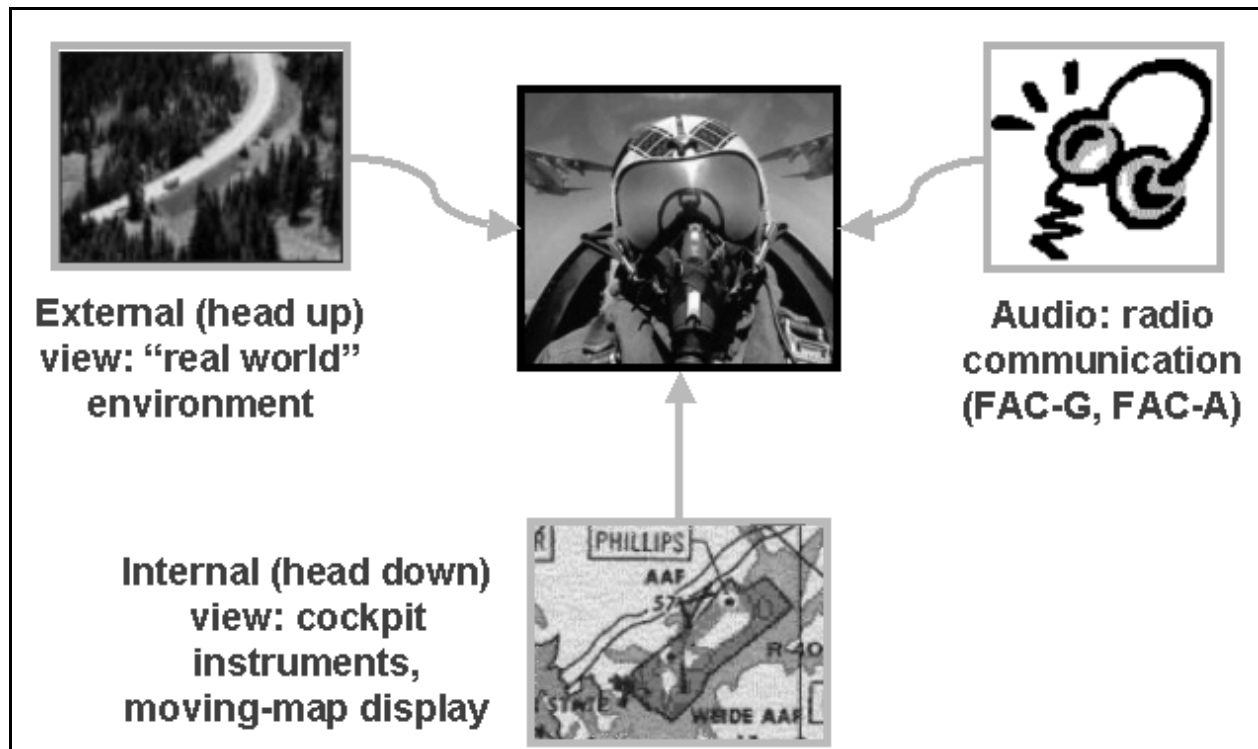
“JSF [the Joint Strike Fighter program] is looking at using a ‘virtual world’ to combine database information and maps in a heads-up or helmet-mounted display to funnel the [CAS] guy in. On TAMPS [Tactical Aircraft Mission Planning System], he can type in a ridgeline to view, and the ridgeline would be highlighted. OK, here’s the river, etc., to cue the pilot. You can’t do this with targets, because they might be moving.”

Without the benefit of highlighting, a target can be very difficult to find. Because of this, CAS pilots historically have relied on FAC-G troops to manually mark the location (if possible) with flares (Gunston and Peacock, 1989). Obviously, this method is highly undesirable if there is any chance for enemy troops to extinguish the flare – and possibly the FAC! Virtual highlighting of a feature (e.g., on a map display) eliminates that opportunity for an enemy to detect the FAC. Three types of virtual highlighting have been shown to improve target acquisition performance by reducing search time: luminance, flashing, and color (Conejo and Wickens, 1997), with color generally accepted as the most effective method (e.g., Yeh and Wickens, 1997).

Unfortunately, highlighting can hinder the pilot if the highlighted object is not actually the correct target – i.e., if the highlighting is invalid (Conejo and Wickens, 1997; Fisher, et al., 1989). Highlighting is most valuable (in reducing search time) when trying to find a target against a complex and unfamiliar background, since it reduces the need for the pilot to scan the entire complex visual field. Conversely, highlighting is least valuable when finding a target against a simple or familiar background, since the pilot’s scan time (without highlighting) would be much shorter, and the potential benefits of highlighting would be less significant.

### 3. Cognitive Process Model

The focused pilot interviews helped to identify several channels of information that a military pilot uses to make critical decisions during air-to-ground missions, including the pilot's external "head up" view of the real world; the internal "head down" view of cockpit instrumentation, and audio input such as radio communication (figure 3-1).



*Figure 3-1. Primary channels of information used by pilots during air-to-ground missions.*

Figure 3-2 presents a more detailed cognitive process model developed to help visualize how a pilot might sense, perceive, integrate and correlate the many – and sometimes disparate – sources of information to support decision-making and ultimate control of the aircraft. As shown in this model, the pilot receives visual information about the real world from the external view through the cockpit window, which is perceived in three dimensions. Different features in this view exist in various focal planes (near, midrange, far) and can be hidden or partially obscured by weather or terrain. A HUD, superimposing navigational and guidance features on the external scene, may supplement this real-world view.

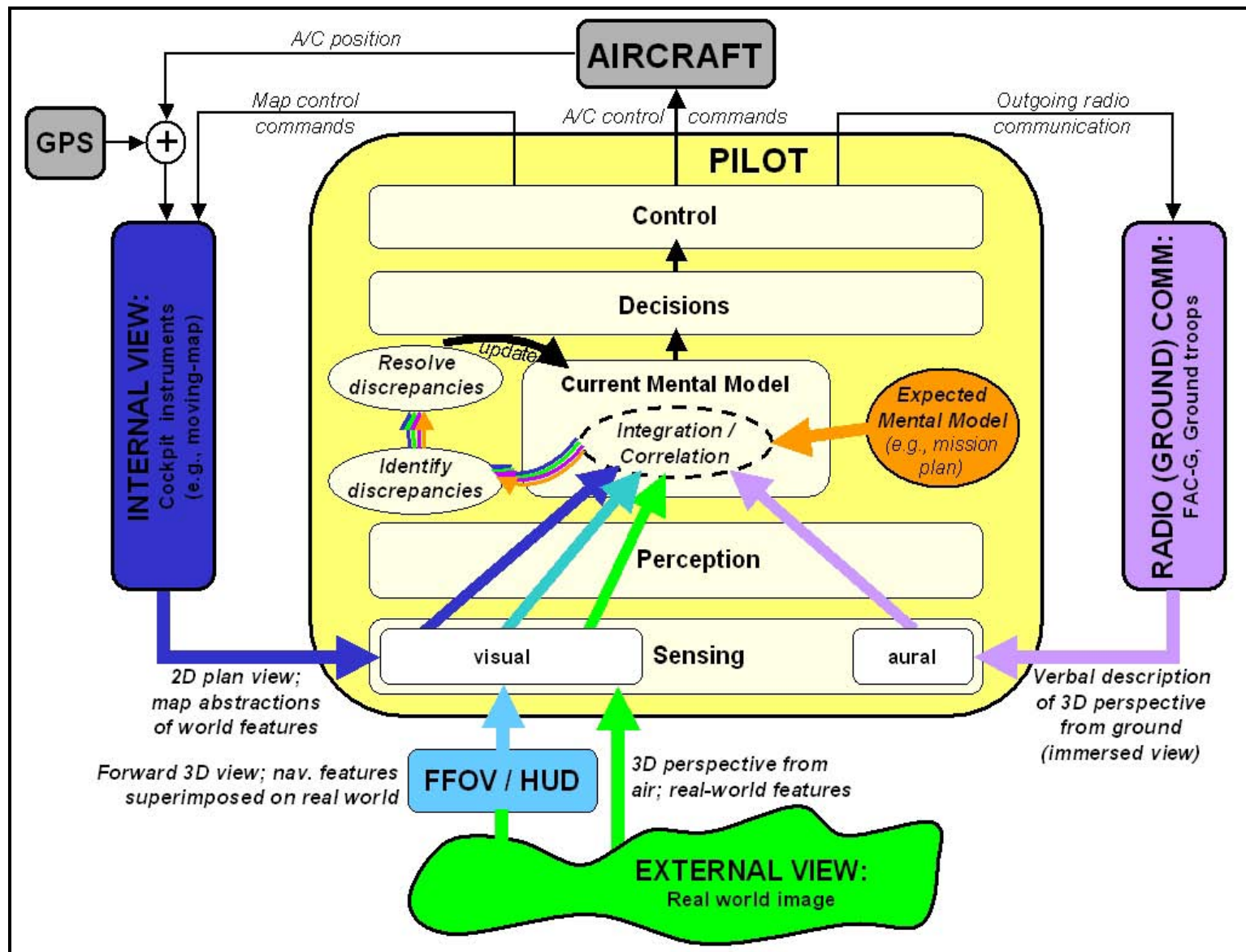


Figure 3-2. Cognitive process model of how a pilot senses, perceives, integrates and correlates various sources of information to support decision-making and ultimate control of the aircraft.

The pilot receives additional visual information from “internal” cockpit instruments, such as gauges and displays. The military pilots interviewed for this project utilized a moving-map display, which presented geospatial abstractions of real-world features in a 2D plan view. The pilot must correlate these 2D abstracted map features on the internal display with 3D real features in the external FFOV to successfully guide the aircraft to the intended target location and, ultimately, acquire the target.

In addition to multiple channels of visual input, the pilot receives audio information from radio communications with the ground (e.g., FAC-G), other aircraft (FAC-A), or a crewmember (e.g., the navigator in a 2-seat aircraft). In the case of a FAC-G / CAS mission, in which the CAS pilot is attempting to acquire a target based on information relayed by a ground-based FAC, the pilot must integrate and correlate his or her own visual information with the FAC’s verbal description of the target area. The success of the CAS pilot’s mission is highly dependent on 1) how well the FAC describes the target and surrounding area and translates this viewpoint (an immersed view from the ground) to the pilot’s overhead perspective; and 2) how well the CAS correlates his or her own views (internal and external) with the FAC’s verbal description.

As shown in figure 3-2, one more channel of information with an impact on the pilot’s mission is the pilot’s own expectations – his or her expected mental model – of the target area and the target itself. This mental model is developed during mission planning, which would have taken place prior to takeoff or – under tight time constraints – while enroute to the mission area. The pilot’s mental model is continuously updated as new information (internal and external) becomes available throughout the mission. As one pilot discussed during his interview, a poor mental model (based on erroneous, preconceived ideas about what to expect) can mislead the pilot and thwart the mission.

The proposed cognitive process model reinforces the importance of a CAS pilot’s skill in transitioning between internal and external guidance to reach the intended target area and acquire the target. A central hypothesis for this thesis is that well designed, shared cues between a CAS pilot and his or her FAC will improve this transition process and contribute significantly to the success of the air-to-ground targeting mission.



## 4. Experiments

### 4.1 Introduction

Three experiments were designed to better understand which visual cues in a moving-map display or HUD can best help a pilot 1) navigate to a given target area (the “flight guidance” phase of a mission) and 2) search for, find and identify a target (the “target acquisition” phase). The author hypothesized that in the case where the target is stationary and in a known location, the most important cues would be those that support the pilot’s guidance to the target area. If the target had moved, the pilot would still need flight guidance cues, but he or she also would need target acquisition cues, which should be shared between the pilot (e.g., CAS) and the ground controller (e.g., FAC-G) to facilitate communication between the crewmembers about the new target location. Sharing information between civilian pilots and ground controllers has been shown to improve situation awareness for both agents, foster collaboration, improve negotiations and decision-making, and reduce operational errors (e.g., Farley, et al., 1998; Hansman and Davison, 2000). Presumably, similar benefits could be gained by sharing relevant information between FAC-G and CAS in the military air-to-ground scenario.

The first experiment, Experiment A, was a quick test of whether pilots would perform better (during flight guidance and target acquisition phases) with a turn in the route or on a straight-line approach to the target area. This experiment primarily served to establish baseline performance measurements and workload assessments for each subject during the two mission phases. In both cases, subjects were presented with a moving-map display that included the following graphic overlays as visual cues: planned flight path, target location, own aircraft location, and a breadcrumb trail (updated once per second) to show the actual flight path. A simulated HUD was also provided, with graphics embedded in the pilot’s forward field of view (FFOV) to represent the planned flight path and the target location. (Detailed descriptions of the moving-map and HUD are provided in the Methods section.) Flight guidance performance was expected to be better on the straight route, especially for subjects with little or no previous flight experience. However, target acquisition performance was expected to be better with a turn in the route, since the turn itself (i.e., the flight path displayed on the moving-map and HUD) would provide distance and heading cues that should assist the subject in locating the target.

Experiment B concentrated on the moving-map display and provided no HUD symbology. This experiment tested how well pilots would perform with three different displays:

1. Combination display: displaying both a topographic map and graphic overlays of the flight path and the last known target location,
2. Map-only display: displaying the topographic map with no graphic overlays, and
3. Overlays-only display: displaying the overlays with no underlying map.

Detailed descriptions of the displays are provided in the Methods section, below. Pilots were expected to perform best with the combination display, since this option provided the most cues about where the flight path and target would be. Better performance was expected with the overlays-only display than the map-only display, theorizing that overlays provided information that was more mission-specific, while also presenting a less cluttered display, than the map.

Experiment C focused on the relative merits of the HUD vs. the heads-down moving-map display to support flight guidance and target acquisition. Pilot performance and workload were compared for the following cases:

1. The *no-HUD* case provided subjects with a moving-map display (with both the topographic map and overlays presented in Experiment B) but with no HUD symbology. This case required subjects to perform a forward mental rotation of the track-up image into the FFOV in order to align the two views, as described in Aretz (1991).
2. The *HUD* case included the same moving-map display as in the previous case plus the HUD symbology presented in Experiment A. In this case, no forward rotation was required since the required symbology was already present in both the map and the FFOV.
3. The *HUD with north arrow* case included the same moving-map and HUD symbology as the previous case, plus a north direction arrow over the target location on the HUD.

Each subject flew two missions for each of the three test cases: one mission in which the target had not moved from its last known location (marked on the moving-map and HUD, if provided) and another in which the target had moved a short distance. At approximately 2 km from the target, the experimenter (acting as a FAC-G) told the subject (acting as CAS) whether the target had moved and, if so, how far and in what direction. For stationary targets, the biggest

improvement in performance was expected between the *no-HUD* and the *HUD* cases, with very little (if any) performance differences between the *HUD* and *HUD with north arrow*. For targets that had moved, significant performance differences were expected between the *no-HUD* and *HUD* cases and between the *HUD* and *HUD with north arrow* cases, since the addition of a north arrow should help the subject orient him or herself within the scene and find the target.

The following sections first describe the methodology common to all three experiments, including a description of the participant population; apparatus; design of the moving-map display, HUD scenery, and targets; experimental procedure; and dependent variables measured. Each experiment is then described in detail, including an overview of procedures specific to the experiment, hypotheses, and results.

## **4.2 Methods**

### **4.2.1 Participants**

Twelve volunteers were recruited from the Naval Research Laboratory (NRL) detachment at the Stennis Space Center, MS. Nine subjects were male, and three were female. Two subjects had a pilots' license, although neither had flown in several years. Three other subjects had experience with flight simulators. Subjects ranged in age from 24 to 52, with an average age of 37.8.

### **4.2.2 Apparatus**

A Dell Latitude C800 laptop computer running Microsoft Flight Simulator 2002 (FS2002) generated the flight scenery for all experiments. The display resolution was set to 1024 x 768 pixels and 32 bits for true color. A Dell Inspiron 4100 laptop computer running the Navy Portable Flight Planning System (NPFPS) FalconView program generated a moving-map at the same resolution and color settings as the FS2002 display. The two laptops were linked via serial cable with software (in Appendix A) developed to perform the following functions:

- Extract positional information from FS2002 in real-time, using a Microsoft Netpipes socket;
- Convert the data to National Marine Electronics Association (NMEA) 0183 compliant GPS strings; and
- Port the GPS latitude and longitude values to the moving-map at a rate of once per second.

Subjects were seated about 2 ft away from both laptops (figure 4-1). The FS2002 display was positioned directly in front of the subject, with the moving-map display to the left and angled toward the subject. A Microsoft Sidewinder Precision 2 joystick was to the right of the laptops and allowed subjects to control pitch, roll, and throttle.



*Figure 4-1. Experimental setup.*

#### 4.2.3 Flight Simulator Settings

To maximize the “outside view” in FS2002, the instrument panel was not displayed. Instead, a simple digital readout of latitude, longitude, altitude, heading, and airspeed were provided at the top of the display. An analog compass was also provided at the top-right corner (figure 4-2). The simulator scene was set for a summer afternoon, with few clouds, no precipitation, unlimited visibility, and no winds. The scenery was located around Waimea Canyon in Kauai, Hawaii, which Microsoft listed as one of the most realistic scenes available for FS2002. Since most subjects had little to no flying experience, the aircraft type was set to a Cessna 172 Skyhawk, which was relatively stable and easy to control. Three levels of outside scene detail were prepared to support various experimental conditions:

- 1) The baseline level (figure 4-2) was simply the original scenery (i.e., what a pilot would see out the front windshield of the virtual cockpit).
- 2) The second level (figure 4-3) provided visual cues in the FFOV to simulate a HUD. Cues consisted of the planned flight path (a series of yellow discs), the location of a FAC-G (a green cone), and the last known location of the target (a red cone). The target itself may or

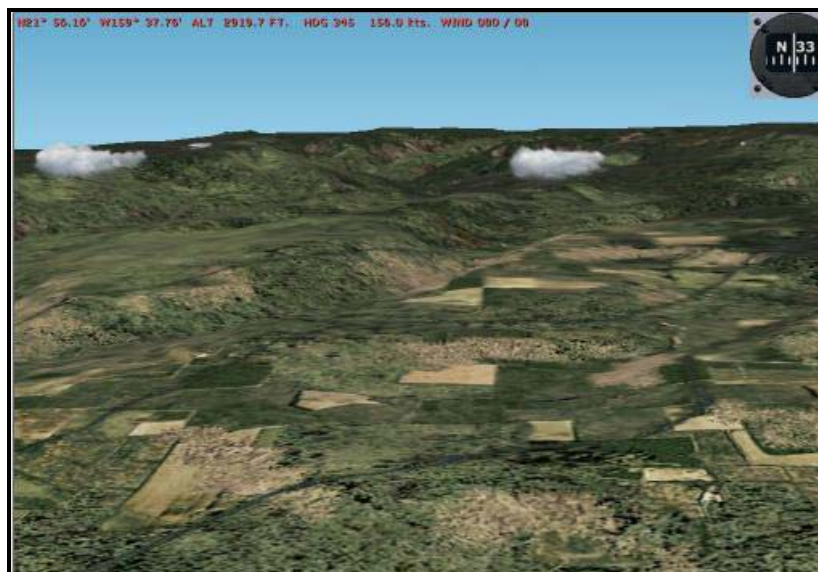


Figure 4-2. FS2002 scenery (baseline level of detail) with instrument readout and compass.

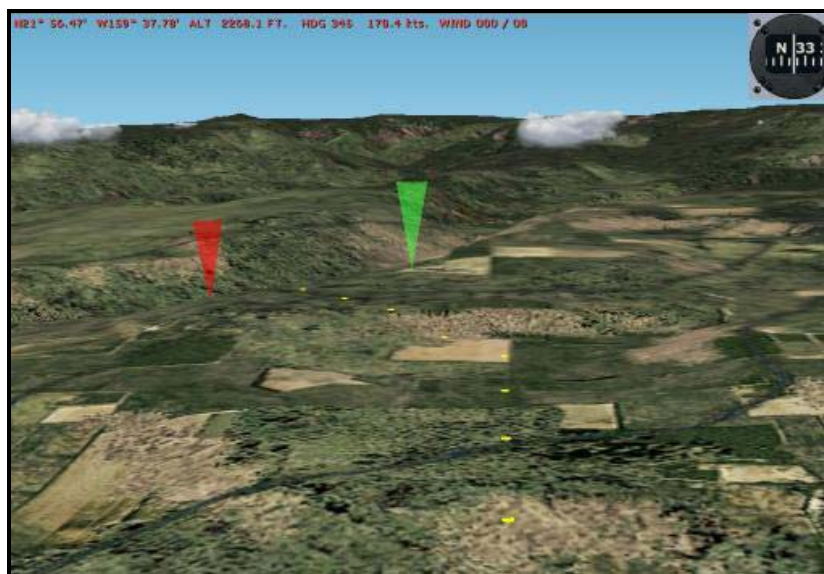


Figure 4-3. Second level of scene detail, with flight path, FAC and target locations as conformal, scene-linked symbols.

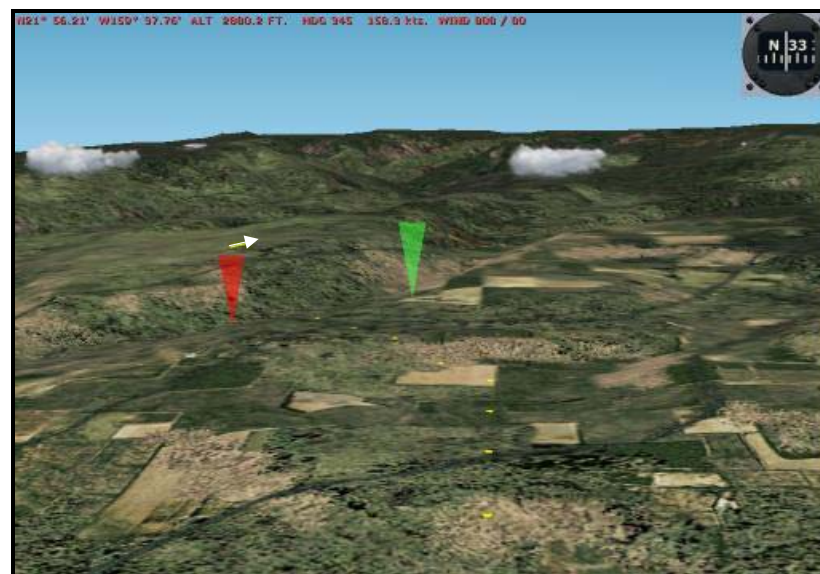
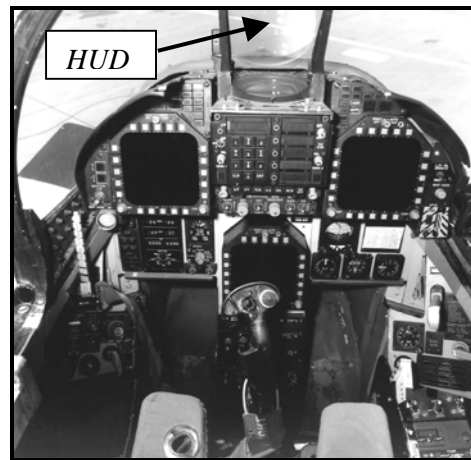


Figure 4-4. Third level of detail shows directional indicator (over the red target cone) in addition to second level symbols.

may not have moved from this designated location by the time the subject reached the target area to begin searching.

- 3) The third level of detail (figure 4-4) provided another cue on the simulated HUD in addition to the previous level: a north directional indicator was rendered as a yellow arrow at the top of the red cone. These cues (flight path, cones, and north arrow) were designed and inserted into the FS2002 scenery using Flight Simulator Design Studio Pro (Abacus Software, 2001).

Note that the simulated “HUD” (figures 4-3 and 4-4) presented in this thesis assumes that the display area completely covers the front window of the cockpit, unlike existing HUDs, which consist of a much smaller display area (figure 4-5). In addition, the HUD symbology presented here is “conformal” (i.e., the flight path and other symbols overlay and move in unison with the outside scene) and “scene-linked” (i.e., the symbols appear to be placed in the actual environment) to minimize the potential hazard of cognitive tunneling associated with a smaller, non-conformal HUD (Foyle, et al., 2002; Hooey, et al., 2001; Yeh and Wickens, 2000).



*Figure 4-5. Current HUD in F/A-18 cockpit.*



*Figure 4-6. Three targets (tank, jeep, fuel truck) and false target (car) used in FS2002 scenes.*

#### 4.2.4 Targets

One of three targets was included in each flight scenario: a tank, a jeep, or a fuel truck (figure 4-6). A car was included in each scene as a false target. These objects also were designed and inserted into the FS2002 scenery using Flight Simulator Design Studio Pro. The four vehicles



were of similar sizes and camouflage colors, such that subjects would be required to scan the target area carefully to find and identify the correct target.

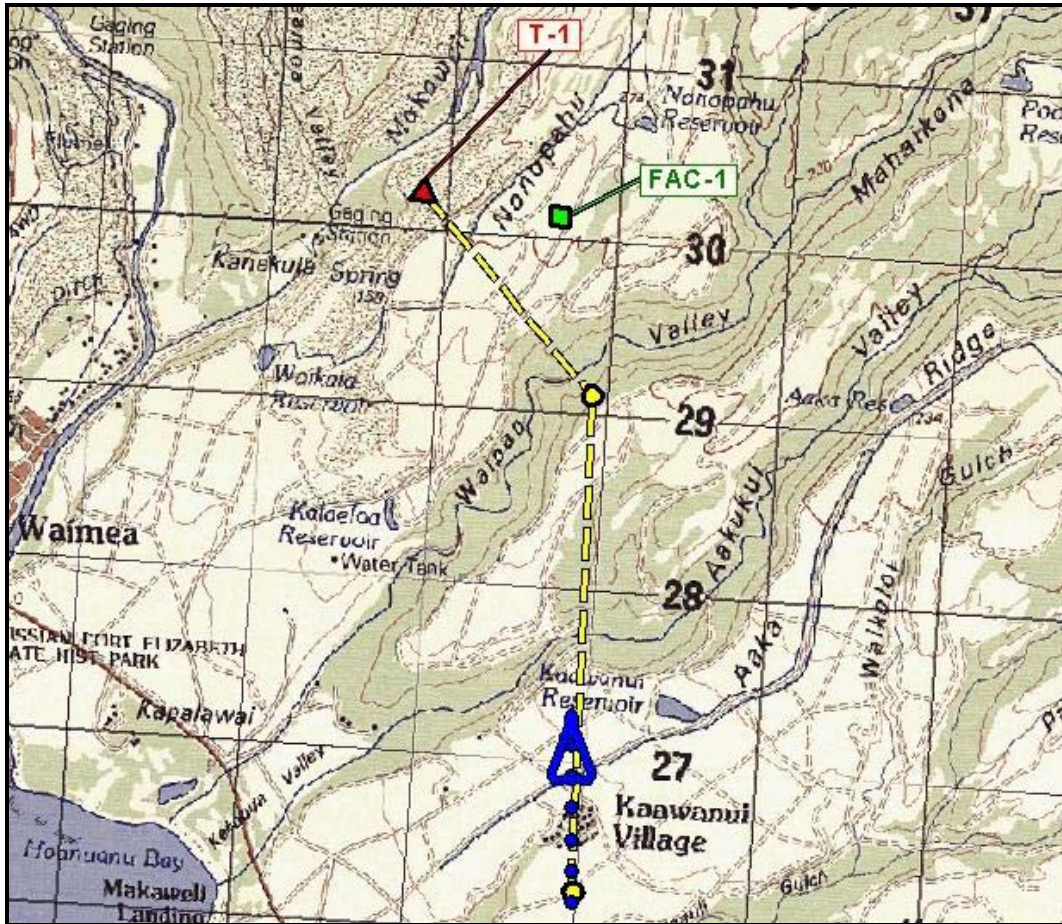


Figure 4-7. FalconView moving-map with color topographic chart of Kauai (10 m / pixel) overlaid with experimental mission symbology: planned route (dashed yellow line), last known location of target (red triangle), location of FAC (green square), current aircraft location (blue triangle), and breadcrumb trail showing actual flight path (blue dots).

#### 4.2.5 Moving-Map Settings

The moving-map consisted of a color topographic chart of Kauai (figure 4-7), which was published by the U.S. Geological Survey (USGS) and downloaded from the Microsoft Terraserver website (Microsoft, 2002) via the Geospatial Information Data Base (GIDB) developed at NRL (2002). The moving-map was set to track-up mode, such that the direction of travel was always towards the top of the display. A triangular icon positioned slightly below the center of the display represented the aircraft's position; the icon was stationary while the map scrolled beneath it. A "breadcrumb trail" indicated where the aircraft had already traveled; the

spacing of the dots in the trail reflected the 1s GPS update rate (i.e., the map updated its position and a new dot was rendered once every second).

Additional symbology used for certain experimental conditions included the planned flight path, the last known location of the target (which may or may not have moved from that location by the time the subject is ready to search for it), and the location of a virtual FAC, also shown in figure 4-7. These symbols were added as drawing overlays within the FalconView software.

#### 4.2.6 Procedure

Subjects were asked to read and sign a consent form, indicating their understanding of their role and the potential risks of participating in these experiments. A copy of the consent form is provided in Appendix D of this thesis. Subjects then were given verbal instructions guided by a prepared set of slides. First, they were shown pictures of the three targets to be found and one false target (figure 4-6). Next, they were told there would be two main phases of each mission: flight guidance and target acquisition. For the flight guidance phase, subjects were given two primary goals: stay alive (i.e., don't crash) and stay on the planned route, usually depicted as a yellow dashed line on the map and FFOV. Secondary tasks were to maintain (or ascend or descend to) a specific altitude, which was given at the start of each mission, and maintain their airspeed between 80-160 knots.

For the target acquisition phase, subjects' primary goals were to stay alive and to find and identify the target as quickly as possible, following instructions that would be given 2 km from the target. Subjects were told that there would be one real target and one false target on each mission. They were told to ignore the false target. They were to search for and say the name of the real target ("tank," "jeep," or "fuel truck") as soon as they could identify it, and to hit the letter "o" on the laptop keyboard as soon as they had confirmation (from the experimenter) that they had correctly identified the target. The "o" is actually a FS2002 command to toggle strobe lights on and off, but in this experiment it was recorded in the flight simulator log file and used later to clock subjects' target acquisition speed from the point at which they had been given instructions (always 2 km from the target). Subjects were told they did not need to follow the planned route after receiving instructions to find the target. If instructions indicated the target



had moved from its last known location, then the subject should deviate from the planned route, if needed, to acquire the target more quickly. If instructions indicated the target had not moved, then staying on the planned route would help them find the target more quickly. Subjects' secondary tasks for the target acquisition phase were to maintain altitude and airspeed, as instructed at the start of each mission.

Each subject flew a training mission consisting of six flight legs and including each of the three targets plus three false targets. The third level of visual detail was provided in the FFOV (figure 4-4) during training, along with the moving-map (figure 4-7). Subjects could fly this mission as often as they wanted before starting the experiment. When they were ready, subjects flew two missions for experiment A, followed by three missions for experiment B and six missions for experiment C. (Experiments are detailed in the Experiment A, B, and C sections, below.)

Subjects were debriefed after each mission. First, they were asked to gauge their workload for each phase of the mission. Workload values ranged from 1 (easiest) to 10 (hardest), based on a modified Bedford Workload Scale (Roscoe and Ellis, 1990), shown in figure 4-8. The references to “additional tasks” in this decision tree are the secondary tasks previously described (i.e., maintain the recommended altitude and airspeed).

Next, subjects were asked to prioritize the cues they relied on to accomplish each of the two mission phases. Valid cues could include any of the following, if available during that mission:

- Outside view (the baseline scenery in the FFOV)
- Additional visual cues in the FFOV (e.g., flight path, target location marker, etc.)
- Flight instrument values (e.g., altitude, heading, airspeed at the top of the FS2002 screen)
- Moving-map display: topographic map
- Moving-map display: mission symbology (e.g., flight path, target location marker, etc.)
- Verbal FAC instructions

Any additional comments that subjects provided were recorded as well.

Subjects were instructed to stop and take a break if they were fatigued or uncomfortable. Most subjects completed all the experiments in a single sitting, which typically lasted about 2 hours.

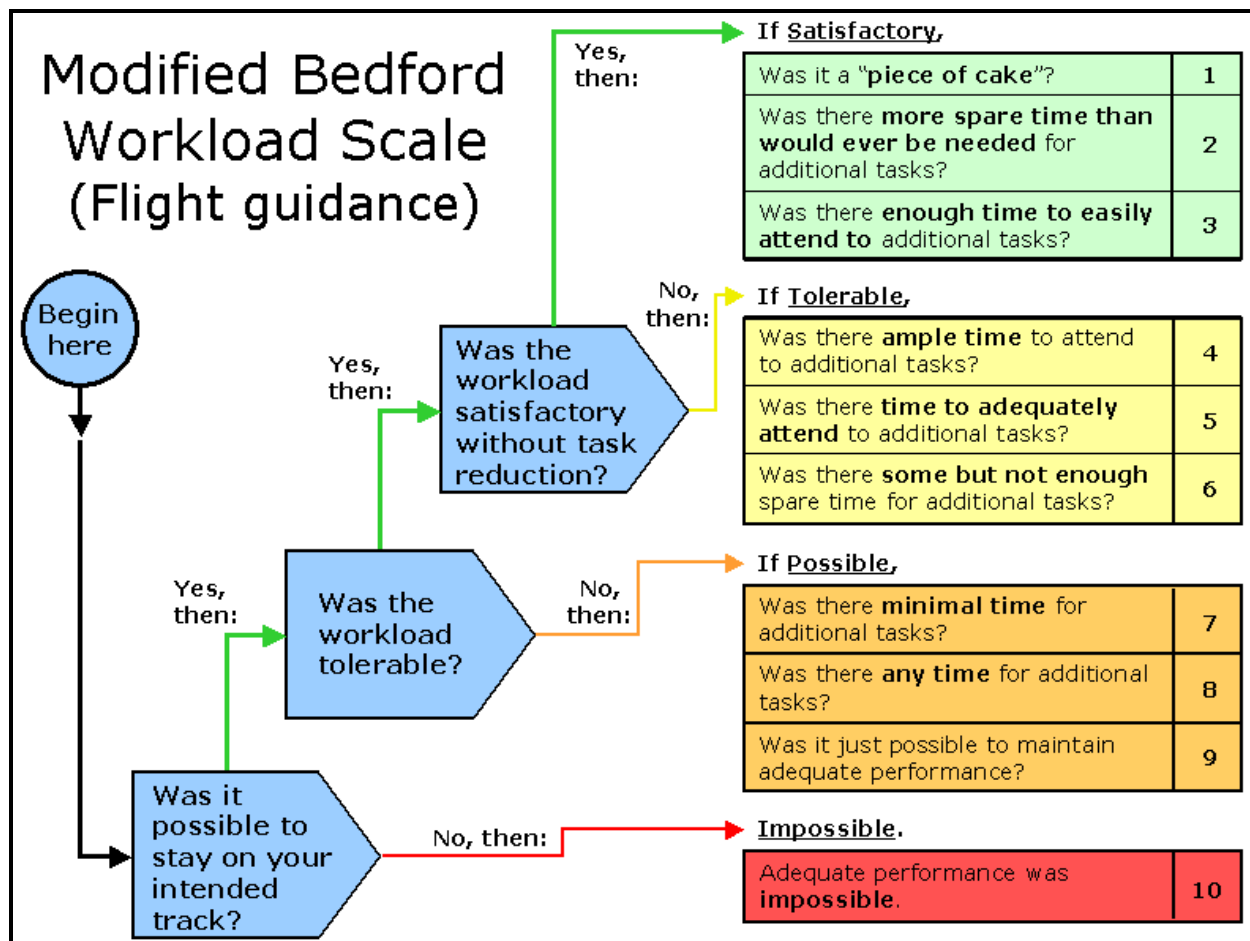


Figure 4-8. Decision tree used to gauge workload during the flight guidance phase of each mission. The same tree was used for the target acquisition phase, except the initial question asked, “Was it possible to find and identify the target?”

#### 4.2.7 Dependent Variables Measured

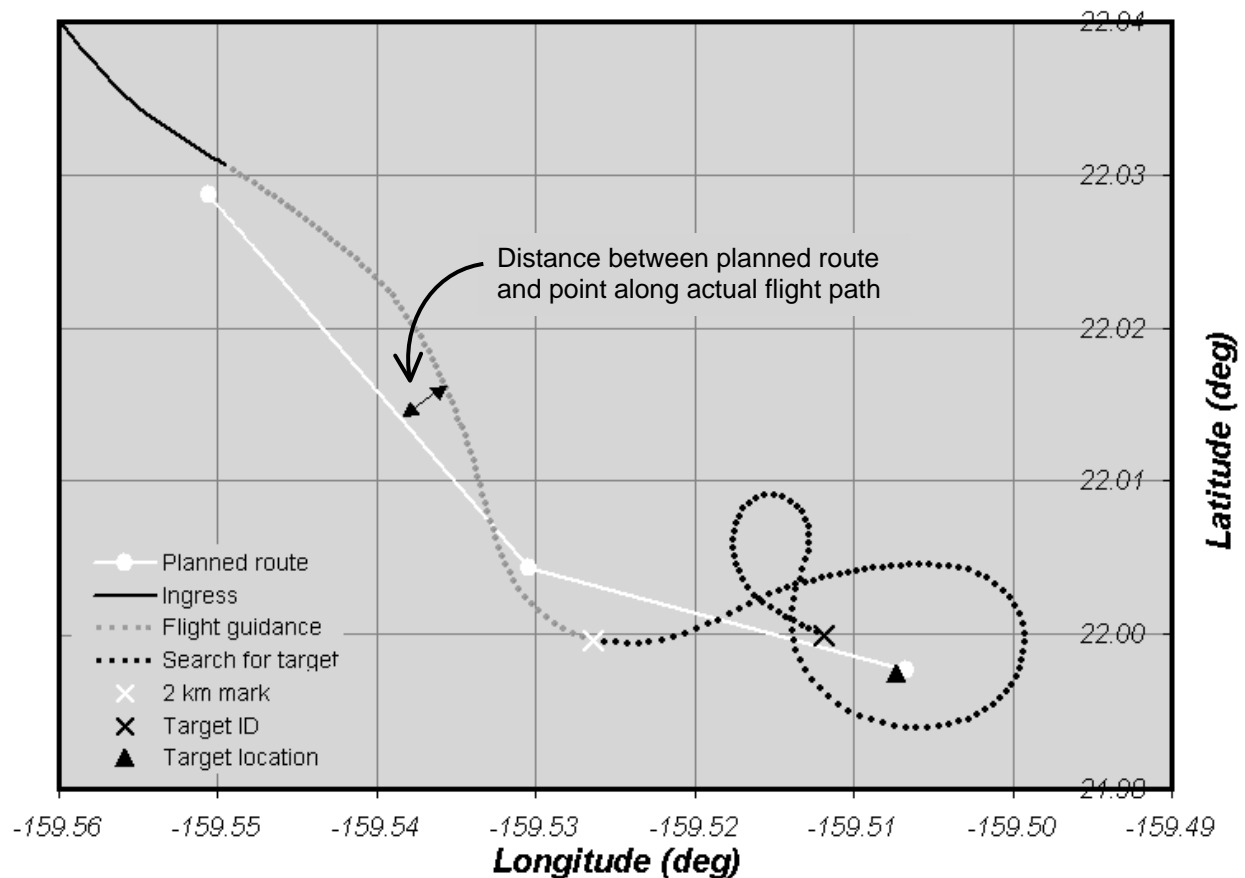
The following information was recorded at 1-second intervals throughout each flight, using the freeware add-on module FLTREC.DLL for FS2002 (Szofran and Hernandez-Ros, 2000):

- Time (clock hour, minute, second)
- Aircraft position (plane latitude, longitude, altitude)
- Airspeed
- Target acquisition (signified by toggling the plane’s strobe lights)

##### 4.2.7.1 Performance

Flight guidance performance was measured in terms of the lateral, perpendicular distance between the planned route and the actual flight path, which was stored as a series of latitude and

longitude points by the flight recorder module (figure 4-9). Specifically, flight guidance performance is represented by the RMSE between the planned and actual flight paths, referred to as RMSE(path). The calculation for this value is provided in Appendix B.



*Figure 4-9. Flight guidance performance is measured in terms of the positive perpendicular distance from the planned route to the actual flight path, averaged over all recorded points (latitude, longitude) along the flight path. Points were recorded at 1-second intervals.*

RMSE(path) is calculated only for the flight guidance phase of each mission (shown as a dotted gray line in figure 4-9), not for the target acquisition phase (shown as a dotted black line), since subjects were told they could deviate from the planned route during target acquisition. RMSE(path) also excludes points along the short ingress leg (shown as a solid black line in figure 4-9), which lasted from the point at which the simulation started until the first waypoint on the flight path, to give subjects 20-30 seconds to get comfortable with the flight and simulated aircraft controls.

Target acquisition performance was measured as the length of time required to find and correctly identify the target, following instructions that were always given 2 km from the target site. If the subject was unable to find the target, the mission was considered a failure.

#### 4.2.7.2 Workload

Workload for both phases was subjectively assessed using a modified Bedford scale (figure 4-8) and objectively measured in terms of altitude and airspeed deviations. Altitude and airspeed were provided as a digital readout at the top of the FFOV (figure 4-2), requiring subjects to temporarily shift their focus away from their primary task to attend to these values. If altitude or airspeed deviated significantly from the planned values, this could be due to an increased focus on the primary task (i.e., decreased focus on altitude or airspeed) and thus, increased workload.

Altitude deviation (figure 4-10) was measured as the RMSE between planned and actual altitude, referred to as RMSE(altitude). All altitude values are in feet above mean sea level. Airspeed deviation was calculated as the RMSE between the outer limits of allowed airspeed (80 - 160 kts) and actual airspeed, referred to as RMSE(airspeed). In other words, if the airspeed remained between 80 – 160 kts, RMSE(airspeed) = 0. All RMSE calculations are provided in Appendix B.

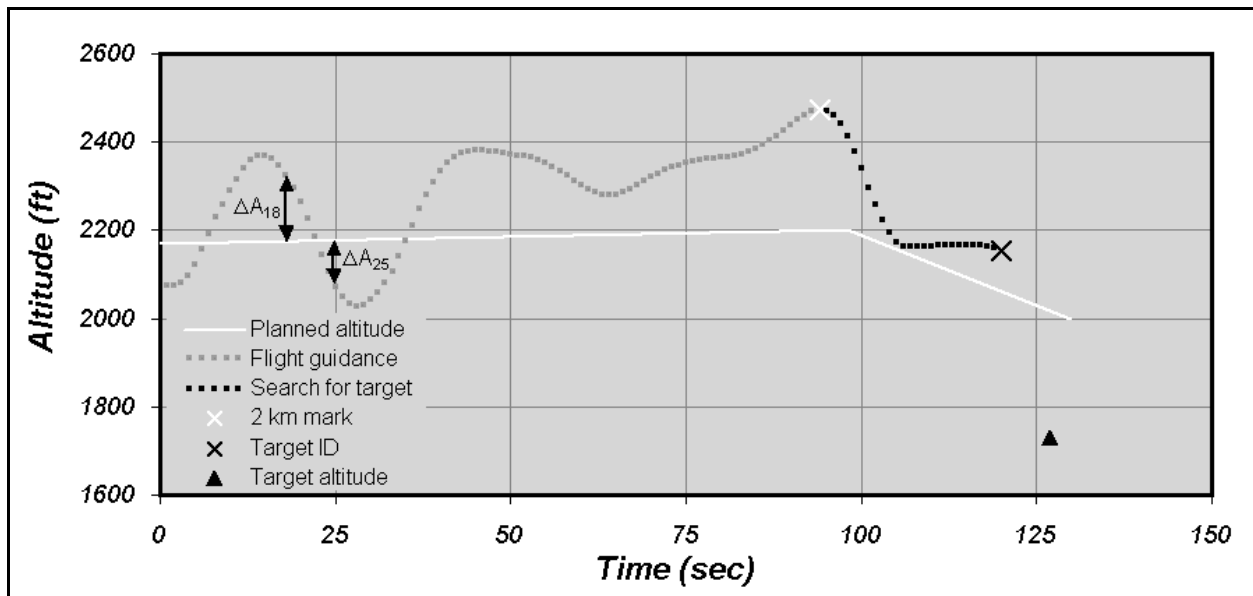


Figure 4-10. Deviation in altitude ( $\Delta A_p$ ) for each recorded point along the flight path. Points were recorded at 1-second intervals. Altitude is above mean sea level.

### 4.3 Experiment A: Route with turn vs. Straight route

#### 4.3.1 Overview

Performance and workload for the two mission phases (flight guidance and target acquisition) are compared for two test cases: 1) flying along a route with a turn, and 2) flying a straight route. Figure 4-11 depicts the two routes used for this experiment. Each subject flew each route once: half of the subjects flew route 1 first, the other half flew route 2 first. The target to be identified in both cases was the tank (to eliminate the effects of target type in this experiment), although subjects were told that each target could be any of the three shown in figure 4-6. The target was always very close to its “last known position” shown on the map and FFOV overlays. In both cases, subjects were shown the second level of detail in the FFOV (figure 4-3), and overlays of the flight path and the last known target location were shown on the moving-map display.

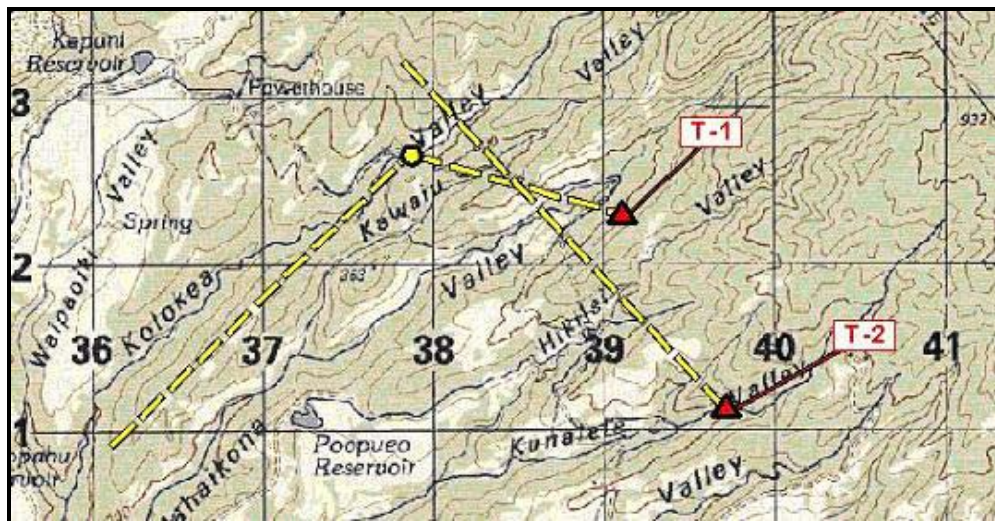


Figure 4-11. Location of routes for Experiment A: one route has a turn, the other does not. Both targets (T-1 and T-2) are tanks.

#### 4.3.2 Hypotheses

Flight guidance performance was expected to be better with the straight route than the route with a turn, especially since the participants had little or no previous flight experience. For the same reason, flight guidance workload was expected to be greater for the route with a turn.

Target acquisition performance was expected to be better with a turn in the route, since the turn itself (with the overlaid mission symbology in the FFOV) should provide cues about distance (improved depth perception) and direction to the target. However, since the target had moved less than ¼ km from its last known location (marked by the red cone in the FFOV), neither performance nor workload was expected to be markedly different between the two routes.

### 4.3.3 Results

All statistical analyses were performed using JMP-IN version 4.0.4 for Windows. Experiment A established baseline measurements for each subject, depicted in figure 4-12 and discussed in the following section. Figures 4-13 and 4-14 summarize performance and workload results of Experiment A, which are discussed after the baseline results. Figure 4-15 presents a summary of the guidance cues used by subjects for each phase (flight guidance and target acquisition) of these flights. Graphs of each subject's performance and workload measurements on each route are provided in Appendix C.

#### 4.3.3.1 *Baseline measurements for subjects*

Figure 4-12 shows performance measurements and workload assessments, averaged over both phases of both routes in Experiment A, by subject. The flights in this experiment were considered comparable to (or easier than) flights in the next two experiments. Therefore, if any subject performed extremely poorly (or extremely well) relative to the general population, then that subject might have been considered an outlier and excluded from all experiments.

To resolve this, a least squares analysis was performed to determine whether the independent variable *subject* contributed more significantly to the outcome of this experiment than *route* (i.e., straight route vs. route with turn). Dependent variables included RMSE(path), time to target, Bedford workload ratings, RMSE(altitude), and airspeed. (RMSE(airspeed) was not used here, because none of the subjects' airspeeds exceeded 160 kts or dropped below 80 kts for any of the routes flown in Experiment A. Thus, RMSE(airspeed) = 0.0 for all subjects in this experiment). Analysis shows that *subject* was a main effect only for Bedford ratings and RMSE(altitude). *Route* was a main effect for all five dependent variables and contributed more significantly to Bedford ratings and RMSE(altitude) than did *subject*. Therefore, none of the subjects will be considered an outlier or removed from the population.

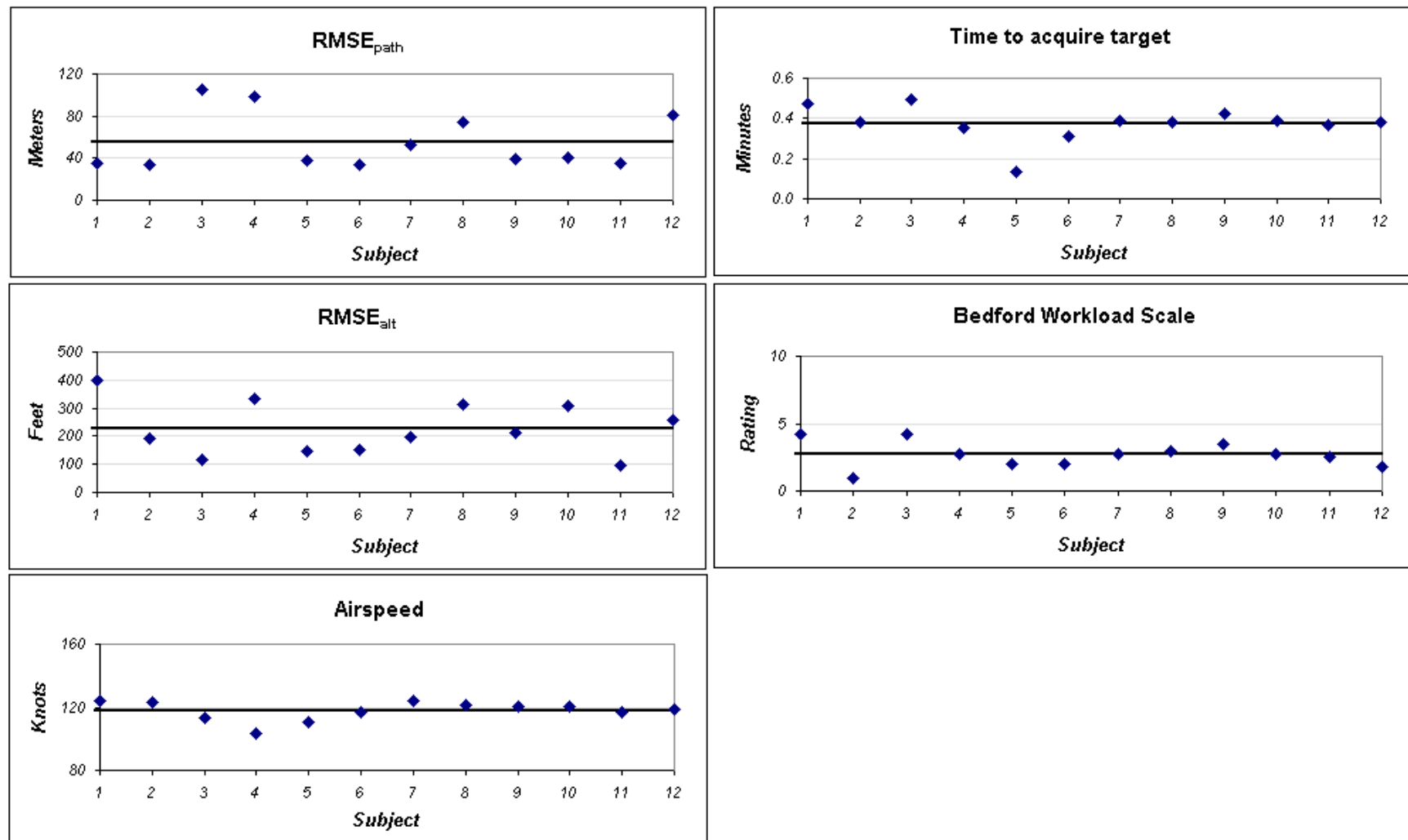


Figure 4-12. Average performance measurements and workload assessments, by subject. Each plot depicts values averaged over both phases of both routes in Experiment A, to provide baseline measurements for each subject.

#### 4.3.3.2 Performance results

The straight route resulted in better flight guidance performance – measured as RMSE(path) and shown by the black line in figure 4-13 – compared with the route with a turn. This was expected, given the general lack of flight experience in this population. However, a T- test did not show this difference to be significant ( $t = 1.28$  with 22 degrees of freedom;  $p \cong 0.22$ ), indicating that on average, these subjects navigated the turn nearly as well as the straight route.

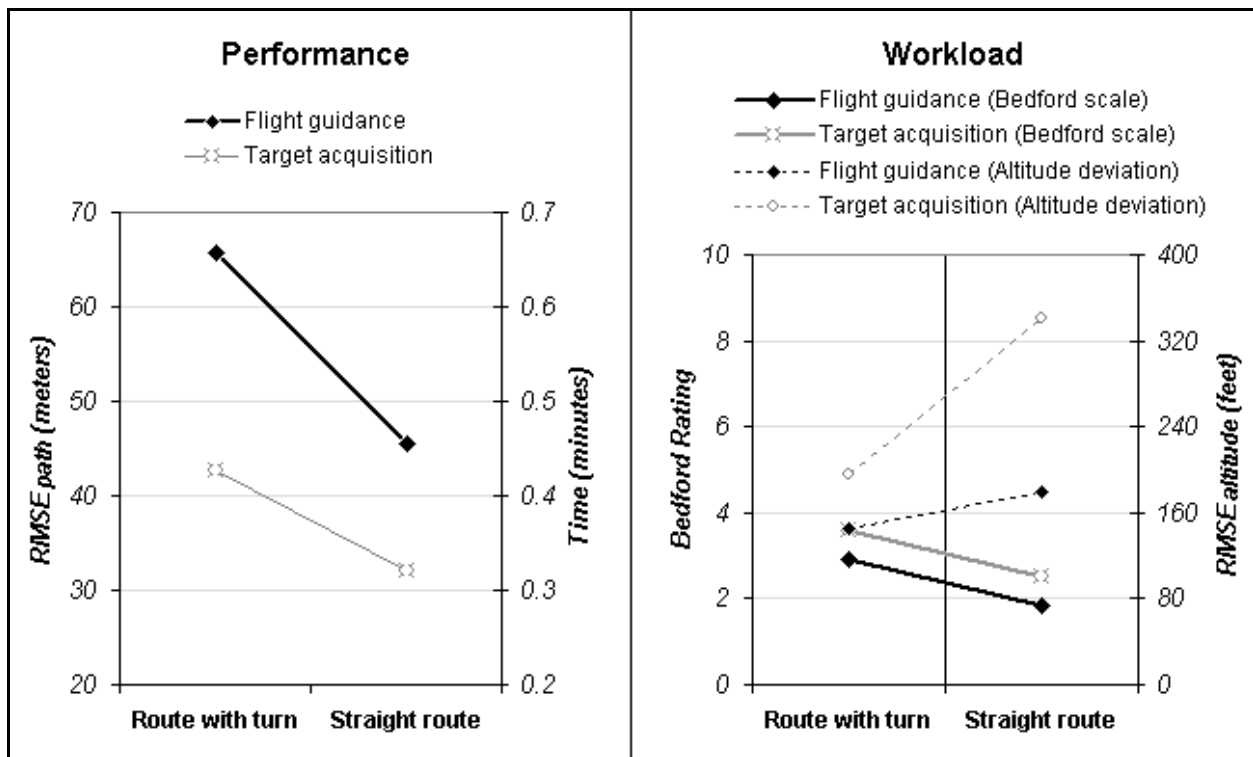


Figure 4-13. Performance results from Experiment A.

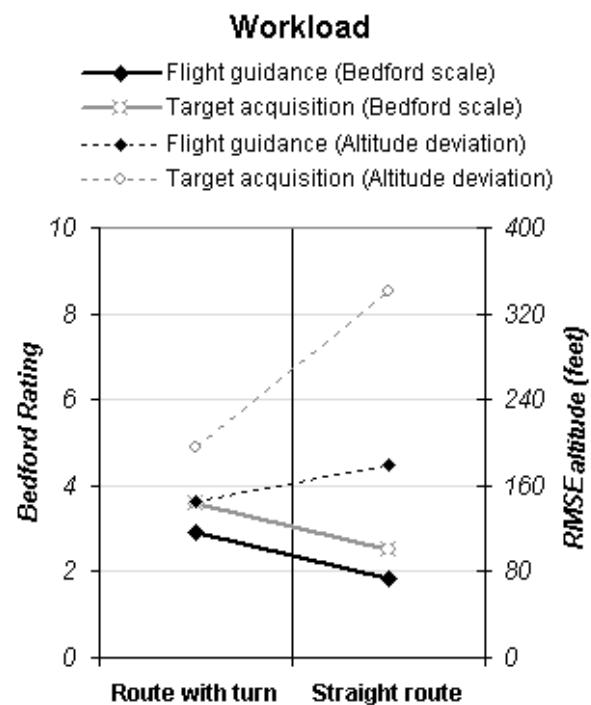


Figure 4-14. Workload results from Experiment A.

Target acquisition performance was measured as time to target (in minutes) and is shown by the gray line in figure 4-13. A T-test revealed that on average, subjects acquired the target significantly faster on the straight route than on the route with a turn ( $t = 2.20$ ;  $p < 0.04$ ), which contradicts the hypothesis. Examination of the flight paths show that a few subjects who had the most difficulty acquiring the target on the route with a turn had initiated their turns late and overshot the second leg of the route. These subjects may have been concentrating on regaining the flight path, at the expense of target acquisition.



#### 4.3.3.3 Workload results

Workload was measured subjectively with a Bedford workload scale and objectively via deviations in altitude and airspeed. Subjects were told to try to maintain a certain altitude (defined at the start of each mission) and to keep their airspeed within a certain range (80 – 160 kts), but that their primary tasks were to stay on the flight path (during flight guidance) and find the target quickly (during target acquisition). If subjects were unable to attend to the small, digital readouts of altitude and airspeed, and subsequently allowed their altitude or airspeed to deviate significantly from the planned values, then workload was assumed higher than if subjects were able to control their altitude and airspeed more precisely.

On average, subjects reported higher Bedford workload ratings on the route with a turn than on the straight route, as expected (figure 4-14, solid lines). A T-test confirms these differences in workload to be significant for both flight guidance ( $t = 2.18$ ;  $p \cong 0.04$ ) and target acquisition ( $t = 1.92$ ;  $p < 0.07$ ). Conversely, subjects averaged higher altitude deviations on the straight route than on the route with a turn, which was not anticipated (figure 4-14, dashed lines). A T-test could not show this difference to be significant for the flight guidance phase, but the difference was significant for target acquisition ( $t = 2.29$ ;  $p \cong 0.03$ ). Altitude deviations might not be a good indicator of target acquisition workload, however, because subjects tended to descend as low as possible (often far below the prescribed altitude) when approaching the target area, to be able to identify the target. In other words, the subjects' deviations in altitude might be *in support of* the primary task of target acquisition, rather than due to a lack of focus on the altitude readout. As previously mentioned, all subjects were able to keep their airspeed between 80 – 160 kts during both flights, suggesting a tolerable workload throughout this experiment.

#### 4.3.3.4 Guidance Cues

Figure 4-15 presents a summary of the cues subjects reported using most frequently during the flight guidance and target acquisition phases of the flights in Experiment A. It is clear that subjects relied more heavily on internal cues (such as the moving-map display and digital readouts of heading, altitude and airspeed) during flight guidance than during target acquisition. Conversely, most subjects switched their attention to primarily external cues (such as the outside scene and conformal HUD-like overlays in their FFOV) during target acquisition. Attention to

FAC instructions also became somewhat important during target acquisition. It is interesting to note that subjects reported using either the map display or digital readouts of heading, altitude and airspeed information, but not both. In other words, subjects did not tend to scan more than two visual cues at a time: either they attended to the FFOV and the map display or the FFOV and the digital readouts.

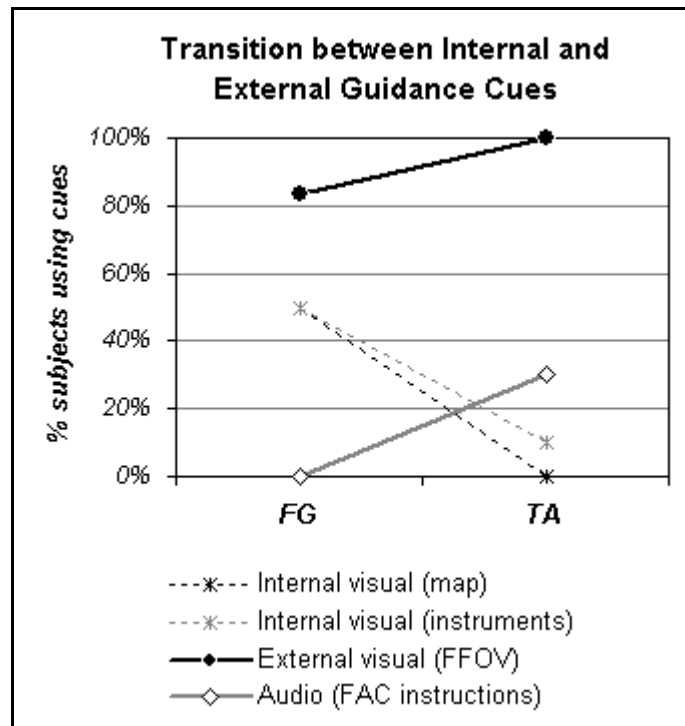


Figure 4-15. Percentage of subjects reporting the use of internal and external visual guidance cues and audio cues during each phase of flight. FG = flight guidance phase, TA = target acquisition phase.

## 4.4 Experiment B: Relative benefits of topographic map and mission symbology

### 4.4.1 Overview

Performance and workload for the two mission phases (flight guidance and target acquisition) are compared for three test cases (figure 4-16):

- 1) Combination display: using a moving-map display with both a topographic map and graphic overlays of the flight path and the last known target location,
- 2) Map-only display: displaying the topographic map with no graphic overlays, and
- 3) Overlays-only display: displaying the overlays with no map.

The target had not moved from its last known location in any of these cases. Subjects were shown only the baseline level of detail in the FFOV (figure 4-2) for this experiment.

*Table 4-1. Order of runs for Experiment B.  
Display C = Combination (map and overlays);  
M = Map only; O = Overlays only.*

*Four missions were flown for each route / display pair.*

	Flight #1		Flight #2		Flight #3	
Subject	Route	Display	Route	Display	Route	Display
1	2	M	3	C	2	O
2	2	M	1	O	1	C
3	1	C	2	M	1	O
4	2	O	1	M	3	C
5	1	O	3	M	1	C
6	2	O	3	C	1	M
7	1	M	3	O	2	C
8	1	C	2	O	3	M
9	3	M	2	C	3	O
10	2	C	3	O	1	M
11	2	M	3	C	1	O
12	2	C	3	M	3	O

Three route and target combinations were prepared (figure 4-17) to minimize subjects' familiarity with the routes and to randomize the targets used for each subject's test flights. All three routes had two legs: a longer first leg (during which flight guidance would be assessed) and a shorter second leg. The turn came approximately 2.7 km prior to the target location, such that the subject would complete the turn just before receiving instructions to find the target. The fuel truck was the target for route 1, the jeep was used for route 2, and the tank was used for route 3.

Each subject flew one route (and searched for one target) for each test case; routes were randomly assigned to each subject's three test cases. Table 4-1 lists the order of runs by subject.

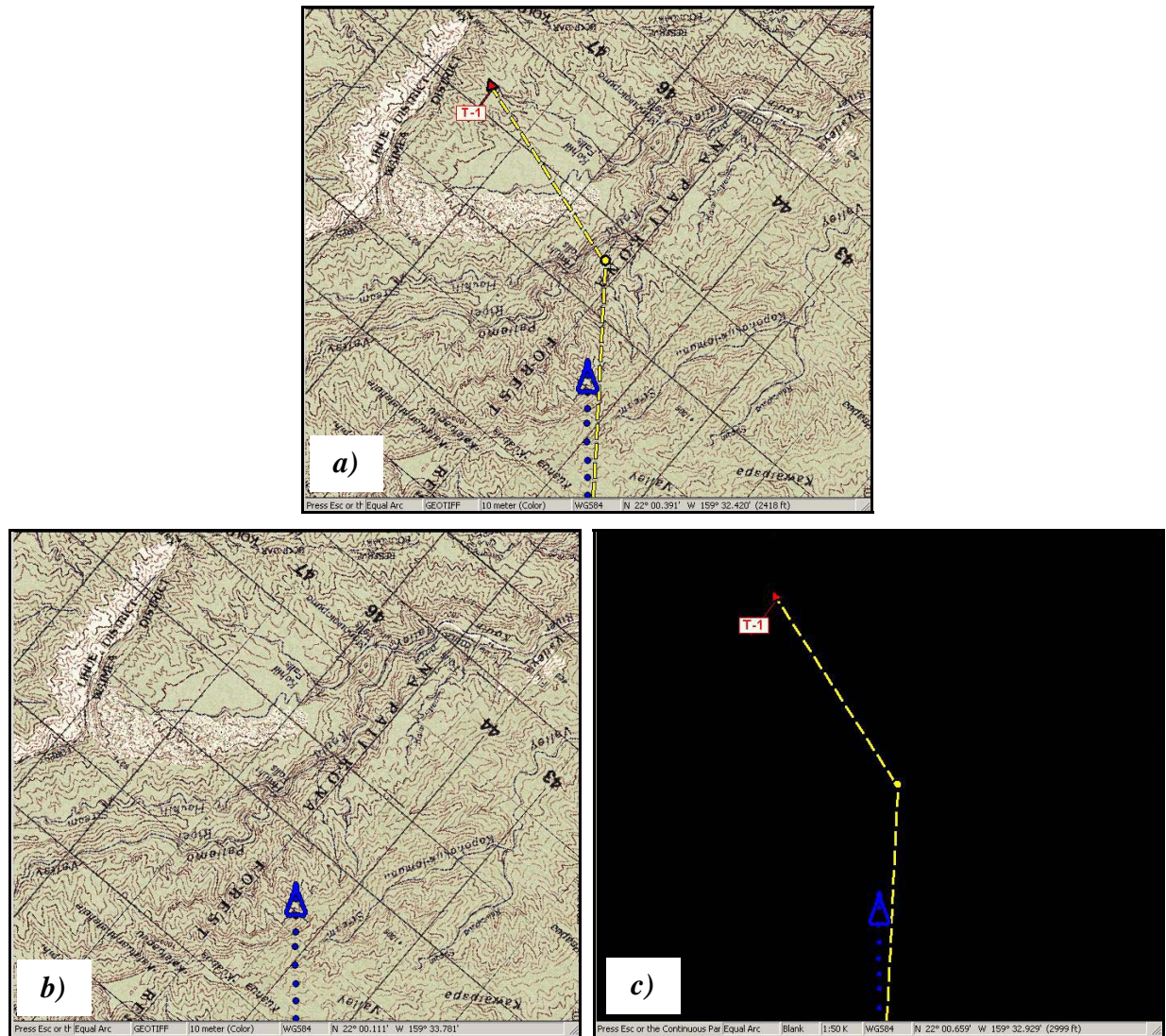


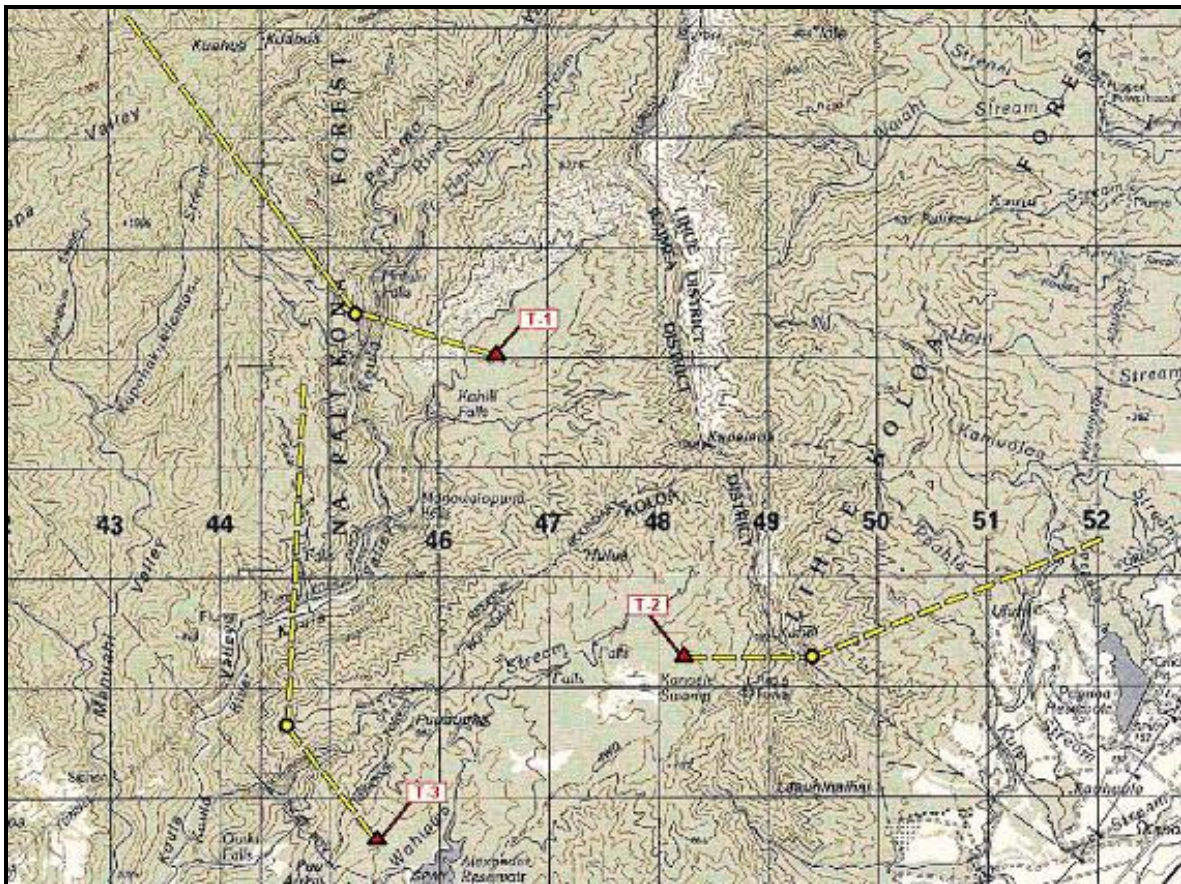
Figure 4-16. Three test cases for Experiment B:  
a) combination of topographic map and graphic overlays; b) map only; c) overlays only.

#### 4.4.2 Hypotheses

Flight guidance and target acquisition performance both were expected to be best with the combination map-and-overlays display, since this option provided subjects with the most cues about where their flight path was and where the target should be. Subjects had enough prior experience with the moving-map during training and Experiment A flights to have developed



some skill at reading and interpreting the topographic map provided. In particular, subjects were expected to be able to correlate the FFOV (hills, ravines, etc.) with the map's contour lines and topography to help them navigate. However, overlays of the flight path and target location were expected to be more useful than the underlying topographic map alone for flight guidance and target acquisition. These overlays also were expected to be much easier to interpret than the map information. Therefore, both flight guidance and target acquisition performance was expected to be better with the overlays-only display than with the map-only display.



*Figure 4-17. Three route / target combinations used in Experiment B. Target T-1 (near the end of route 1) was the fuel truck; T-2 (route 2) was the jeep; and T-3 (route 3) was the tank.*

Both flight guidance and target acquisition workloads were expected to be highest with the map-only display, as subjects focused considerable attention on correlating the FFOV with the map information, without the assistance of clearly defined flight path or target location cues. Workload for the flight guidance phase was expected to be lowest with the overlays-only option,

since the subject simply had to “follow the yellow-brick road” and would not be distracted by trying to interpret the map. Workload for the target acquisition phase was expected to be lowest for the overlays-only display only if the subject found the target on the first attempt. If the subject initially missed the target and had to circle and search for it, then the combination display was expected to be of greater assistance (and result in lower workload) than the overlays-only display in returning to the target area and resuming the search.

#### 4.4.3 Results

Figures 4-18 and 4-19 summarize the results of Experiment B, in which three different route and target combinations (route1-fuel truck; 2-jeep; 3-tank) were used for each display test case. Since some routes might have been more difficult to navigate and some targets more difficult to find, results were averaged by route and target. Graphs of each subject’s performance and workload measurements are provided in Appendix C.

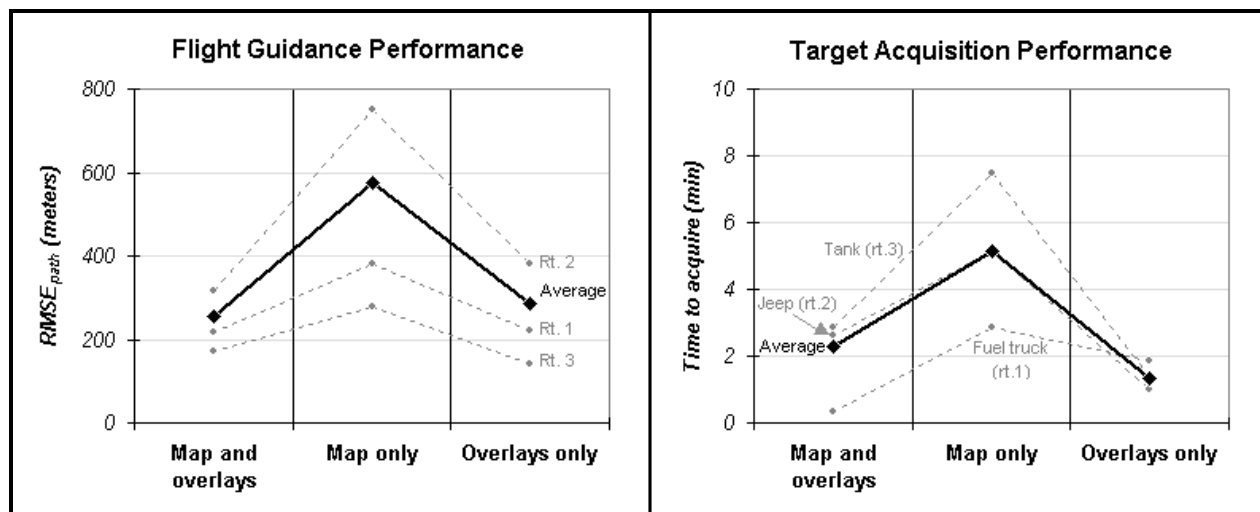


Figure 4-18. Summary of performance results from Experiment B.

##### 4.4.3.1 Performance results

As in the previous experiment, flight guidance performance was measured in terms of RMSE(path). A least squares analysis of the data indicates that display type is a main effect ( $F(2,20) = 14.71, p = 0.0001$ ) on RMSE(path), as is route flown ( $F(2,20) = 14.04, p = 0.0002$ ). As shown in figure 4-18 (left), the map-only display resulted in the worst flight guidance

performance, regardless of route flown, as expected. The overall average RMSE(path) for the map-only display was more than twice that of the combination (map and overlays) display. A pair-wise T-test shows this difference to be significant ( $t = 2.54$ ,  $p < 0.02$ ). RMSE(path) for the map-only display was also significantly greater than for the overlays-only display ( $t = 2.24$ ,  $p < 0.04$ ). Subjects performed equivalently with the combination and overlays-only displays, as expected. However, several subjects said they preferred the overlays-only display to the combination, noting that it was less cluttered and, therefore, less distracting and easier to determine their position relative to the flight path.

Target acquisition performance in Experiment B was measured by the length of time required to find and correctly identify the target, as in Experiment A. Two subjects (#2, #3) were unable to find the target: one while flying route 1 with the overlays-only display, the other while flying route 2 with the map-only display. Since it was impossible to measure time-to-target when the target was not found, and since neither display type nor route / target was common to the two cases, these subjects were considered outliers and removed from the population before performing a least squares analysis on target acquisition data.

Figure 4-18 (right) presents average target acquisition results by display and target type, after removing both outlier subjects' results. For all three targets, average performance was worst with the map-only display, which supports the hypothesis. Least squares analysis indicates that display type is a main effect ( $F(2,16) = 4.05$ ,  $p < 0.04$ ) for time to target (neither subject nor route / target type were main effects). Pair-wise T-tests show that the average time to acquire a target while using the map-only display was significantly longer than while using the overlays-only display ( $t = 2.24$ ,  $p < 0.04$ ) and longer than while using the combination display ( $t = 1.65$ ,  $p \cong 0.11$ ). Average time to target with the combination display was somewhat longer than with the overlays-only display, but this difference is not significant ( $t = 1.45$ ,  $p < 0.17$ ).

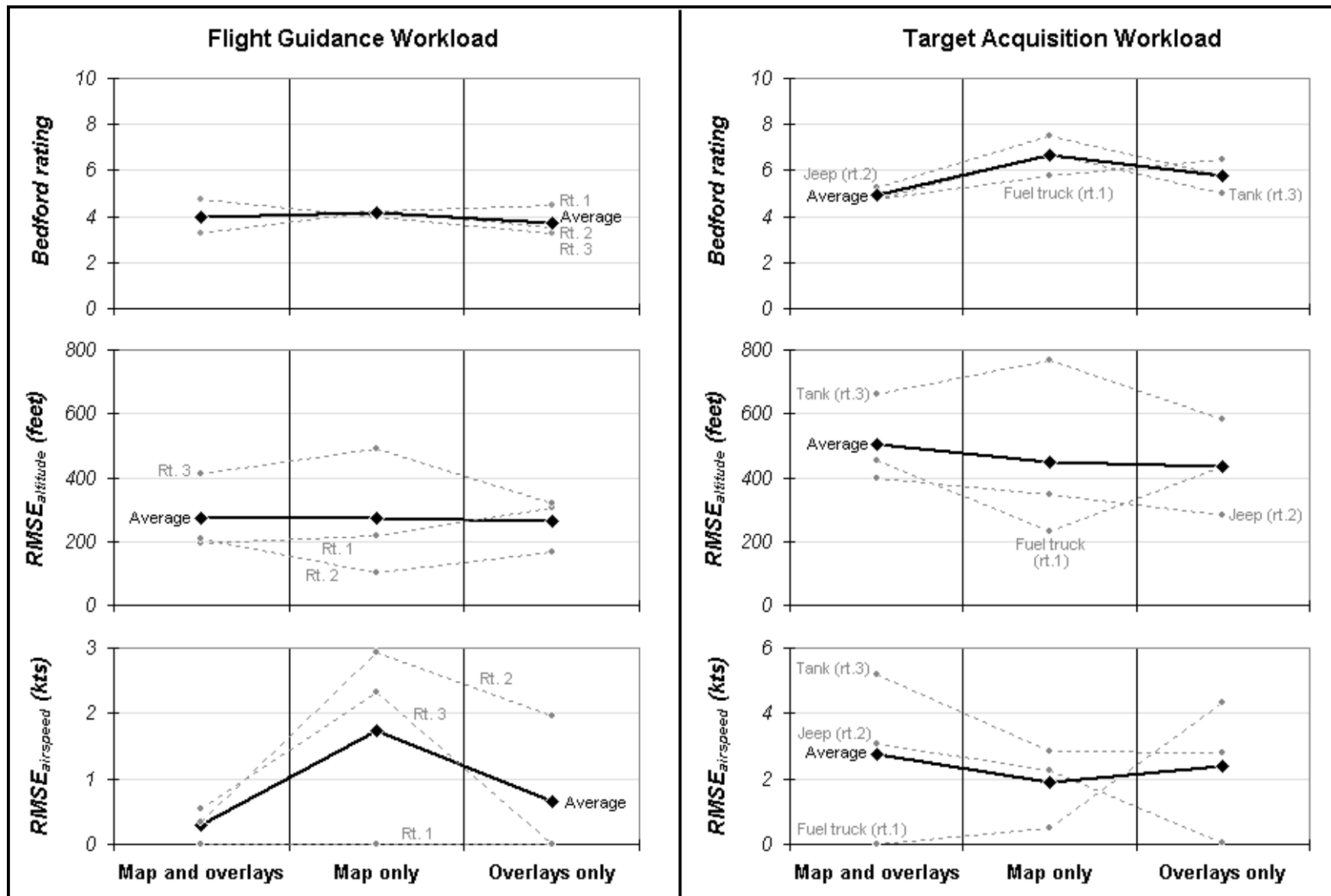


Figure 4-19. Summary of workload results from Experiment B.



#### 4.4.3.2 Workload results

Figure 4-19 (left) presents subjective (Bedford scale, top) and proposed objective (altitude and airspeed) workload results for the flight guidance phase. A least squares analysis confirmed that display type is a main effect for RMSE(airspeed):  $F(2,20) = 3.66, p < 0.04$ . On average, subjects exceeded the prescribed airspeed limits more frequently with the map-only display than with either the combination or overlays-only display. A T-test revealed a significant difference in RMSE(airspeed) between the map-only and combination displays ( $t = 1.782, p < 0.09$ ), but no significant difference between map-only and overlays-only displays. Display type does not appear to influence either Bedford ratings or altitude. Altitude was primarily influenced by route flown; Bedford ratings were not affected by any of the independent variables in this experiment.

Figure 4-19 (right) presents workload results for the target acquisition phase. None of the three proposed workload indicators (Bedford, altitude and airspeed) appears to be significantly related to display type. A least squares analysis failed to identify display type as a main effect for altitude or airspeed (both of which were primarily influenced by the route flown or target found), but it suggested that display type might influence Bedford ratings. A T-test revealed a significant difference in average Bedford ratings between the map-only display and the combination display ( $t = 1.92, p < 0.07$ ), suggesting that subjects thought they were working harder with the map-only display than with the combination display, as expected. No other differences in Bedford ratings were significant. As in the flight guidance phase, the route flown (and respective target sought) proved to be the main effect for both altitude and airspeed. As in Experiment A, deviations in altitude do not appear to be a very good indicator of workload during target acquisition. Again, this is likely because subjects tended to descend as low as possible to find the target.

#### 4.4.3.3 Guidance Cues

Figure 4-20 presents a summary of the cues subjects reported using during the flight guidance and target acquisition phases of each flight in Experiment B. As in Experiment A, subjects relied much more heavily on internal cues during flight guidance than during target acquisition. With a map-only display, subjects mostly referred to the instrument readings (heading, altitude, airspeed) for their internal guidance cues; with the overlays-only and combination (map and

overlays) displays, subjects referred mostly to the map display for internal cues. As in Experiment A, most subjects did not use both the map display and the instrument readings together for a given phase of flight. With all three displays, subjects switched their attention to primarily external cues (such as the outside scene and conformal HUD-like overlays in their FFOV) and attended less to internal cues during target acquisition. Attention to FAC instructions again was more important during target acquisition than flight guidance.

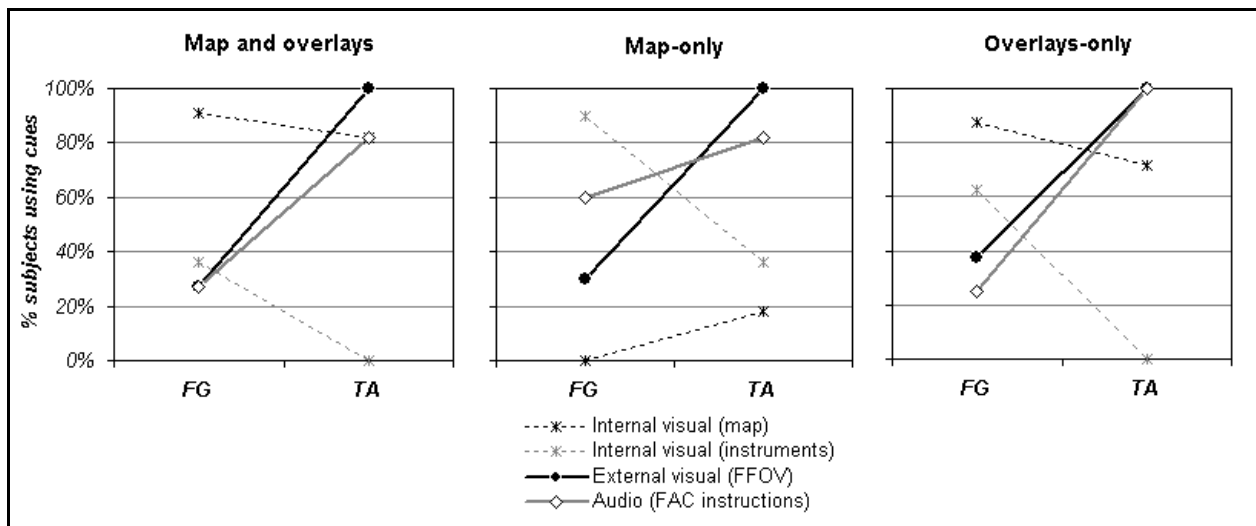


Figure 4-20. Percentage of subjects reporting the use of internal and external visual guidance cues and audio cues during each phase of flight, for each of the three displays tested in Experiment B. FG = flight guidance phase, TA = target acquisition phase.

## 4.5 Experiment C: Acquiring target with HUD vs. without HUD

### 4.5.1 Overview

Flight guidance and target acquisition performance and workload are compared for the following three display cases:

- 1) The no HUD case provided subjects with a moving-map display (as shown in figure 4-7) consisting of a topographic map overlaid with the planned flight path (yellow dashed line), last known location of the target (red triangle), location of the FAC-G (green square), own aircraft location (blue triangle), and breadcrumb trail showing the actual flight path (blue dots, updated once per second). The baseline FFOV level (figure 4-2) was used, consisting of the outside scene but without the flight path or target marker.
- 2) The HUD case included the same moving-map display as in the map-only case plus the second FFOV level (figure 4-3), which provided visual cues to simulate an advanced HUD. Cues consisted of the planned flight path (yellow discs), location of the FAC-G (a green cone), and the last known location of the target (a red cone).
- 3) The HUD+ case included the same moving-map display as in the previous cases plus the third FFOV level (figure 4-4), which added a north direction indicator to the HUD. The north indicator was rendered as a yellow arrow positioned just over the red cone.

Each subject flew two missions for each of the three test cases: one mission in which the target had not moved from its last known location (marked on the moving-map and HUD, if provided) and another in which the target had moved anywhere from  $\frac{1}{4}$  to  $\frac{3}{4}$  km. At approximately 2 km from the target, the experimenter told the subject whether the target had moved and, if so, how far (in km) and in what direction. Prior to the start of this experiment, each subject was reminded that the yellow discs on the HUD (if provided), which highlighted the planned flight path, were spaced  $\frac{1}{4}$  km apart, so this cue could be used to estimate distance on the ground. Subjects also were reminded that they would have up to three sources of directional information: the analog compass and digital heading at the top of the flight simulator screen (figure 4) and, when provided, the north arrow over the red target marker on the HUD.

Table 4-2. Order of runs for Experiment C.

Test cases are no HUD, HUD (including flight path, target marker, and FAC marker) and HUD+ (HUD with north arrow). Target is either stationary (S) or has moved (M).

Subject	Flight #1			Flight #2			Flight #3			Flight #4			Flight #5			Flight #6		
	Route	Case	Target	Route	Case	Target	Route	Case	Target	Route	Case	Target	Route	Case	Target	Route	Case	Target
1	3	HUD+	S	5	no HUD	M	6	HUD+	M	1	HUD	S	2	HUD	M	4	no HUD	S
2	2	no HUD	S	1	HUD+	S	5	HUD	M	3	no HUD	M	6	HUD	S	4	HUD+	M
3	1	HUD	M	3	HUD	S	2	no HUD	M	3	HUD+	S	1	HUD+	M	5	no HUD	S
4	5	HUD	M	3	no HUD	M	6	HUD	S	1	no HUD	S	2	HUD+	M	4	HUD+	S
5	5	HUD+	M	3	no HUD	S	1	HUD	M	3	HUD+	S	2	HUD	S	4	no HUD	M
6	4	HUD	M	2	HUD+	S	6	no HUD	S	1	HUD+	M	3	HUD	S	5	no HUD	M
7	5	HUD	S	1	no HUD	S	3	HUD+	M	2	no HUD	M	4	HUD+	S	6	HUD	M
8	4	HUD	M	1	HUD+	S	5	HUD+	M	2	no HUD	M	3	HUD	S	6	no HUD	S
9	2	no HUD	S	6	HUD+	M	3	HUD	M	5	HUD+	S	4	HUD	S	6	no HUD	M
10	4	HUD+	M	6	HUD+	S	1	no HUD	M	4	no HUD	S	2	HUD	S	6	HUD	M
11	4	no HUD	M	3	HUD	M	1	HUD	S	5	no HUD	S	2	HUD+	M	6	HUD+	S
12	6	HUD+	M	2	HUD	M	3	no HUD	S	1	no HUD	M	4	HUD	S	5	HUD+	S

Six route and target combinations were prepared (figure 4-21) to minimize subjects' familiarity with the routes and to randomize the targets used for each subject's test flights. The tank was the target for routes 1 and 3, the fuel truck for routes 2 and 5, and the jeep for routes 4 and 6. Each subject flew one route (and searched for one target) on each mission; routes were randomly assigned to each subject's six missions. Table 4-2 lists the order of runs by subject.

#### 4.5.2 Hypotheses

Flight guidance and target acquisition performance both were expected to be best with the HUD (with or without a north arrow), since the planned flight path and the last known location of the target were superimposed directly onto the subject's field of view. The north arrow was only expected to be of assistance while acquiring a target that had moved from its last known location.

Both flight guidance and target acquisition workloads were expected to be highest without a HUD, as subjects worked to correlate their FFOV with the map information without the assistance of clearly defined flight path or target location cues in the FFOV. When the target had moved from its last known location, target acquisition workload was expected to be lowest when the north arrow was presented in the HUD. When the target had not moved, both HUD cases were expected to result in comparable workloads.

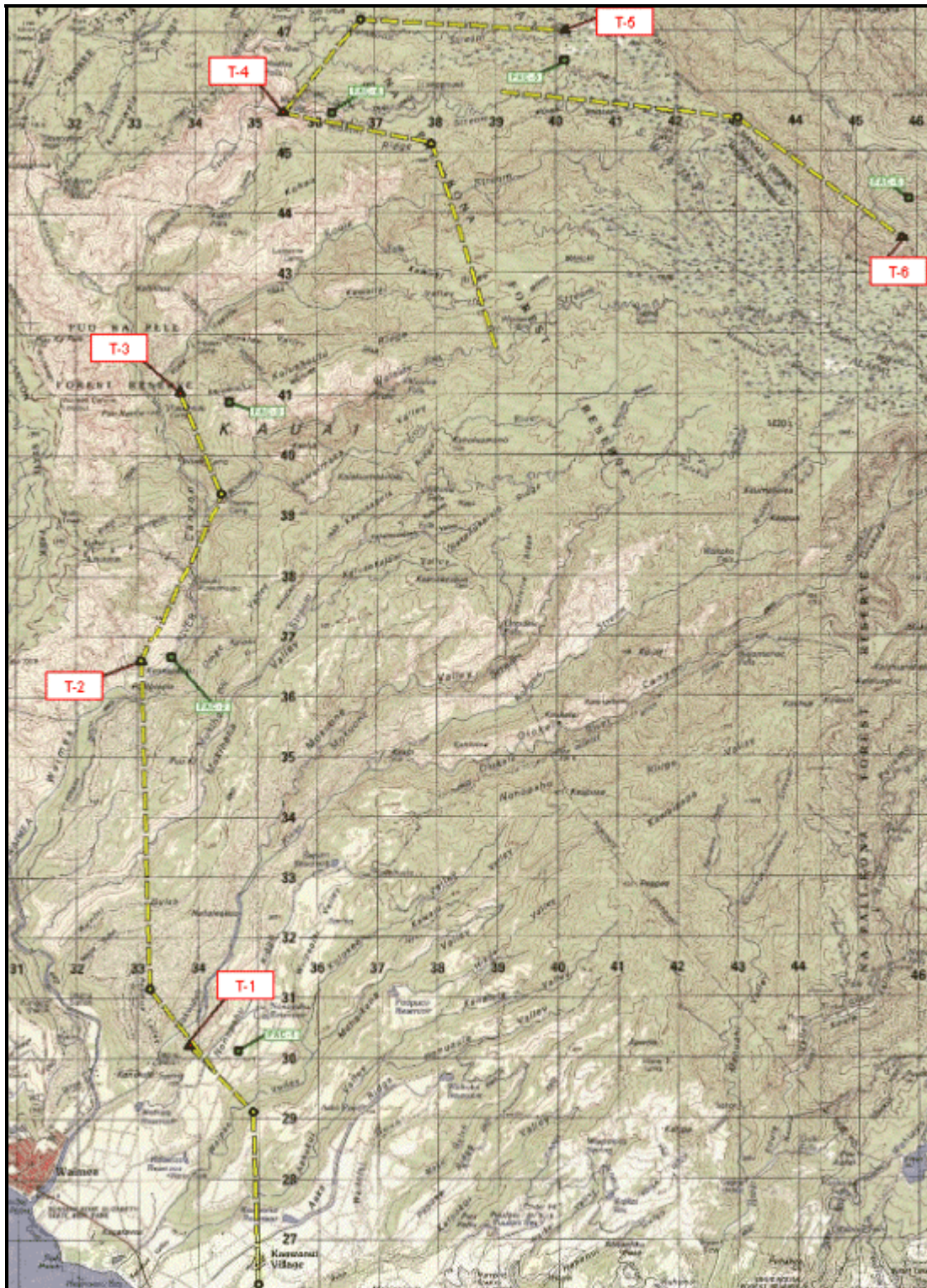


Figure 4-21. Six route / target combinations used in Experiment C.  
 Target T-1 (near the end of route 1) and T-3 (route 3) were the tank; T-2 (route 2) and T-5 (route 5) were the fuel truck; T-4 (route 4) and T-6 (route 6) were the jeep.

### 4.5.3 Results

Figures 4-22 through 4-26 summarize the results of Experiment C, in which six routes and three targets were randomly assigned to each mission. As in the previous experiment, results are presented by route and target, since some routes might have been more difficult to navigate and some targets more difficult to find. Results for individual subjects are provided in Appendix C.

#### 4.5.3.1 Performance Results

Flight guidance performance again was measured in terms of RMSE(path). On average, the HUD cases resulted in better performance than the no-HUD case, as expected (figure 4-22), but a T-test failed to show that this difference was significant ( $t = 1.239$ ,  $p \cong 0.22$ ). A least squares analysis indicates that subject and route were the only main effects for flight guidance performance in this experiment.

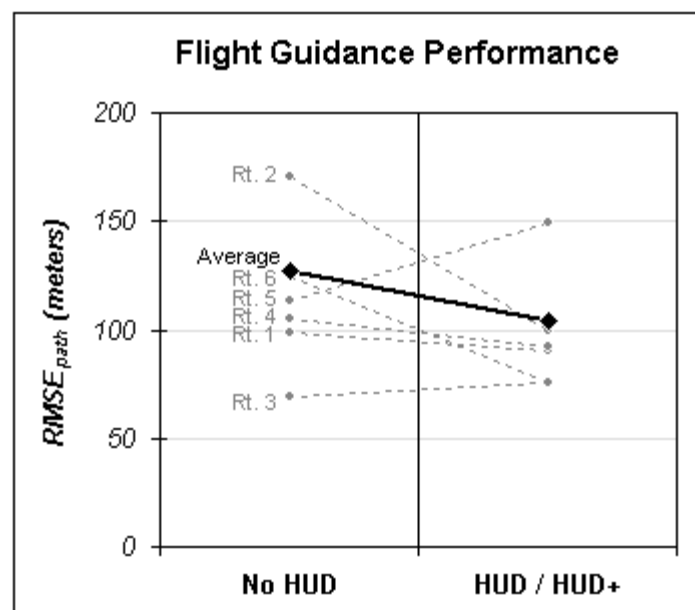


Figure 4-22. Flight guidance performance results of Experiment C.

As before, target acquisition performance was measured by the length of time a subject needed to search for, find, and identify a target located near the end of the planned flight path. Figure 4-23 presents average results for acquiring a stationary target (i.e., when the target was located very close to its marked location on the moving-map display and HUD, when available). Subjects could find a stationary target more than twice as quickly with the experimental HUD symbology (with or without a north arrow) than without, a difference that is significant ( $t = 8.87$ ,  $p < 0.006$ )



and supports the hypothesis. In fact, a least squares analysis indicates that the only main effect on stationary target acquisition time was the presence or absence of HUD symbology. The inclusion of a north arrow on the HUD had no significant effect on stationary target acquisition, also as expected, since subjects had no need for directional information beyond that provided by the red target location cone (present in both HUD and HUD+ cases).

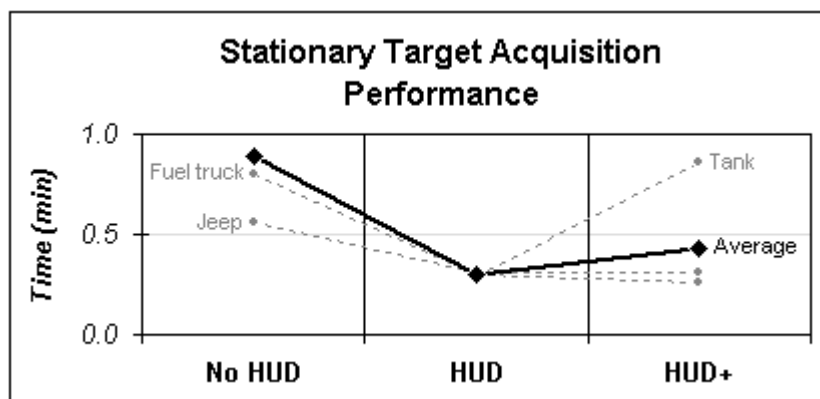


Figure 4-23. Stationary target acquisition performance results of Experiment C.

Figure 4-24 presents average results for acquiring a target that had moved a short distance ( $\frac{1}{4}$  -  $\frac{3}{4}$  km) from its marked location on the moving-map display and HUD, when available. (The reader should note that the target was not actually moving in the simulation; movement was assumed to have occurred before the subject entered the target area.) Two subjects (#5, #7) were unable to find the target: one while flying route 4 (target: jeep) without a HUD, the other while flying route 3 (target: tank) with a HUD and north arrow. Since it was impossible to measure time-to-target when the target was not found, and since the two cases used different displays, routes and targets, these subjects were considered outliers and removed from the population before performing a least squares analysis on the remaining target acquisition data.

Figure 4-24 suggests that subjects were able to acquire the target most quickly with the enhanced HUD (with north arrow), but it also suggests that the HUD without north arrow produced the slowest target acquisition time. Given these conflicting results, it is not surprising that a least squares analysis could not show that either the HUD (vs. no HUD) or the north arrow (vs. no north arrow) had any significant effect on target acquisition time when the target had moved from its expected location.

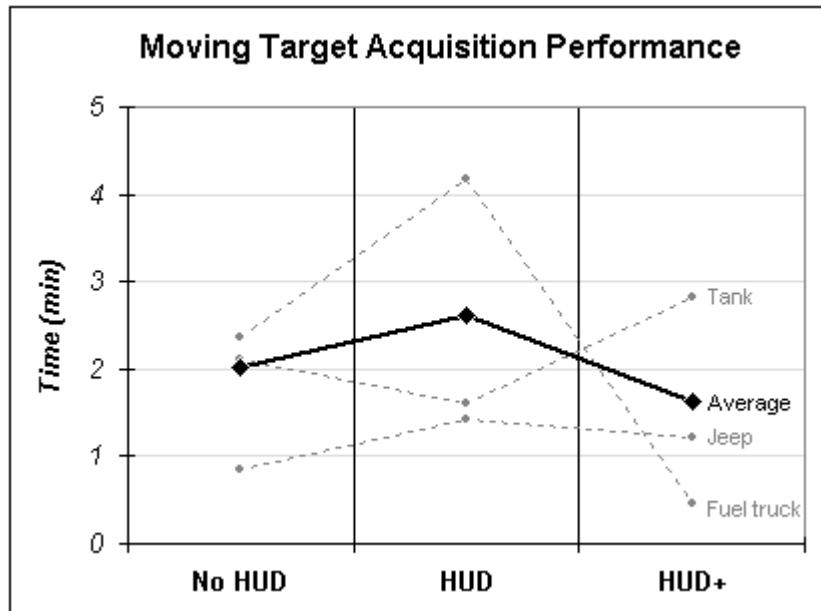


Figure 4-24. Moving target acquisition performance results of Experiment C.

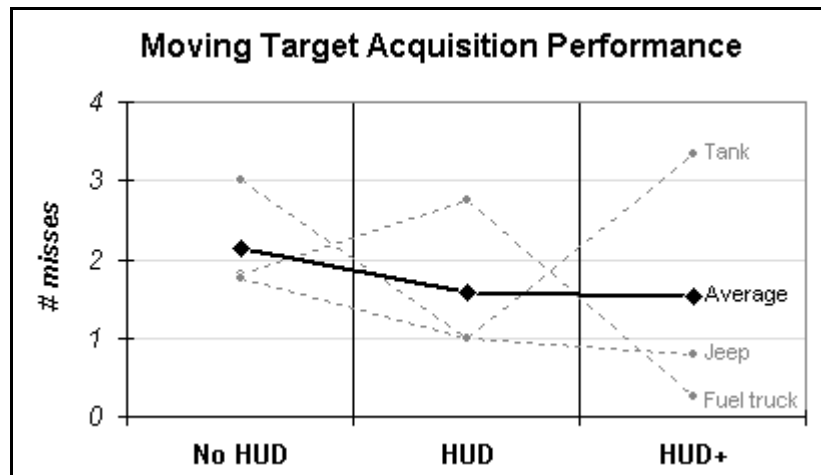


Figure 4-25. Average number of missed attempts to find target, when target had moved from its last known location.

Another measure of target acquisition performance was considered in this case: the number of times a subject flew over the target area (missing the target) before finally acquiring the target. This measure would remove the effects of flight guidance skills, since some subjects were more comfortable and capable of performing tight turns than other subjects. For example, one subject might miss the target only once, but take a long time circling around to acquire the target on the next attempt. Another subject might miss the target several times, but be capable of circling



tightly and therefore acquire the target in a shorter period of time. Figure 4-25 shows the average number of missed attempts, for each display type. Again, the enhanced HUD (with north arrow) produced the best performance (i.e., fewest missed attempts before finally acquiring the target). This time, the no-HUD case produced the poorest performance, as expected. However, a least squares analysis still could show no significant correlation between the results and display type.

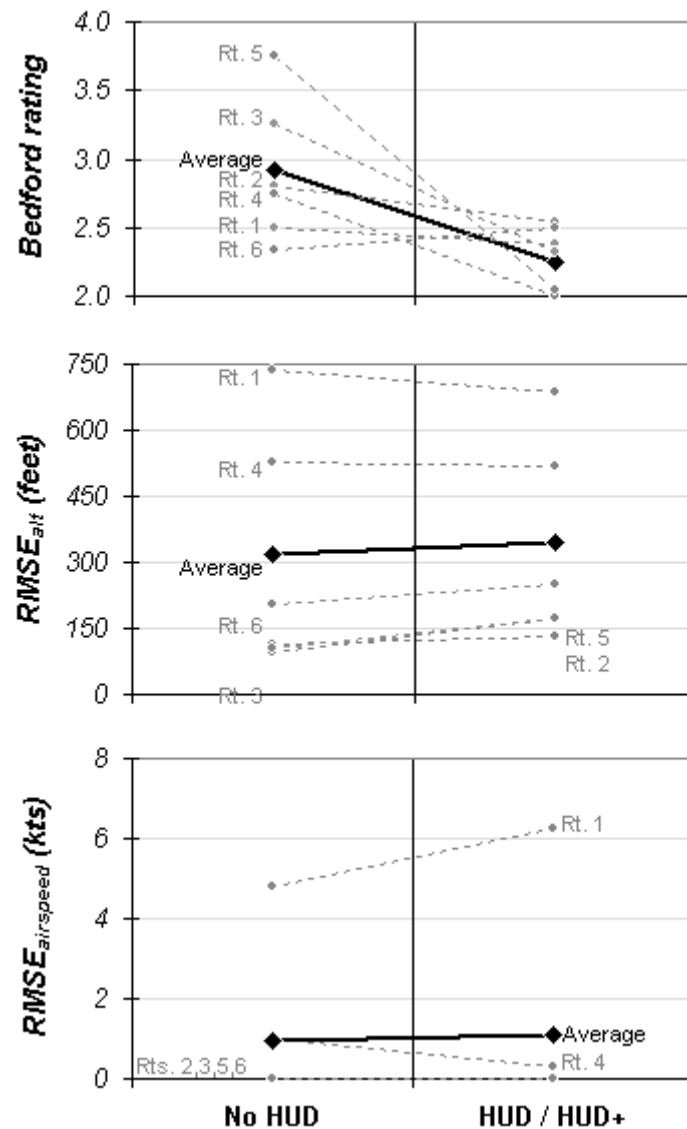


Figure 4-26. Flight guidance workload results of Experiment C.

#### 4.5.3.2 Workload Results

Figure 4-26 presents subjective (Bedford scale, at top) and objective (altitude and airspeed deviation) workload results for the flight guidance phase. Least squares analysis indicates display type (no HUD vs. HUD/HUD+) has a main effect on Bedford workload ratings ( $F(1,59)=7.94$ ;  $p<0.007$ ), but not on either altitude or airspeed (both of which were primarily influenced by route flown). On average, subjects reported their workload with the HUD or HUD+ to be about 75% that without a HUD, a difference that is significant ( $t = 2.44$ ;  $p < 0.02$ ) and supports the hypothesis. The presence of a north arrow in the HUD had no significant effect on any of the flight guidance workload indicators, as expected.

Figure 4-27 (left) presents workload results for acquisition of a stationary target. As in the flight guidance phase, least squares analysis indicates that display type (no HUD vs. HUD/HUD+) is a main effect for Bedford workload ratings ( $F(1,23)=16.54$ ;  $p=0.0005$ ), but not for either altitude or airspeed. (Route is the main effect for both altitude and airspeed). On average, subjects reported their workload with a HUD to be 65% that without a HUD, a difference that is significant ( $t = 3.66$ ;  $p < 0.0009$ ) and supports the hypothesis. Whether or not the HUD included a north arrow had no significant effect on stationary target acquisition workload, as expected.

Figure 4-27 (right) presents workload results for acquisition of a target that has moved a short distance from its last known location. In this case, the workload indicators (Bedford ratings, altitude, and airspeed) seem to conflict with one another: each suggested that a different display produced the most work. A least squares analysis indicates that display type (no HUD vs. HUD/HUD+) is not a main effect for any of the workload indicators, although display type had some effect on Bedford ratings. Route is the only main effect for altitude and airspeed. On average, subjects reported their workload with a HUD to be 79% that without a HUD, but this difference is not significant. Whether or not the HUD included a north arrow had no significant effect on target acquisition workload when the target had moved, which contradicts the hypothesis.

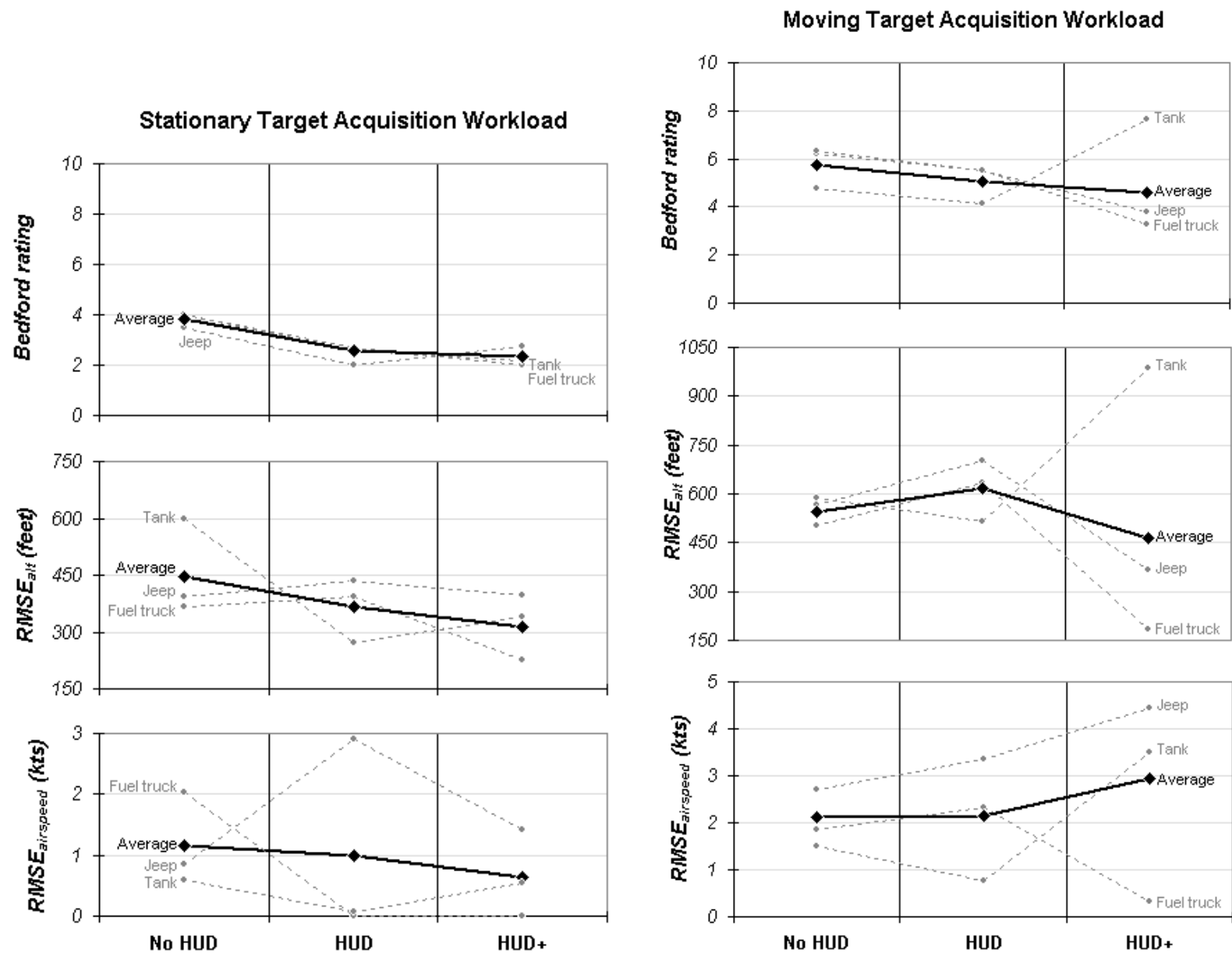


Figure 4-27. Target acquisition workload results of Experiment C.

### 4.5.3.3 Guidance Cues

Figure 4-28 presents a summary of the cues subjects reported using during the flight guidance and target acquisition phases of each flight in Experiment C. As in the previous two experiments, subjects relied more on internal cues during flight guidance than during target acquisition, and they relied more on external cues during target acquisition than during flight guidance. In this experiment, it is clear that the map display plays a more significant role in target acquisition when there are no virtual cues in the FFOV (the no-HUD case) than when the necessary cues are provided in the FFOV (the HUD and HUD+ cases). Also in the no-HUD case, very few subjects used external visual cues during flight guidance; all subjects relied on the map display for most of their flight guidance information when the HUD was absent. Finally, more subjects relied on the map display and FAC instructions when the target had moved from its expected location than when the target had not moved.

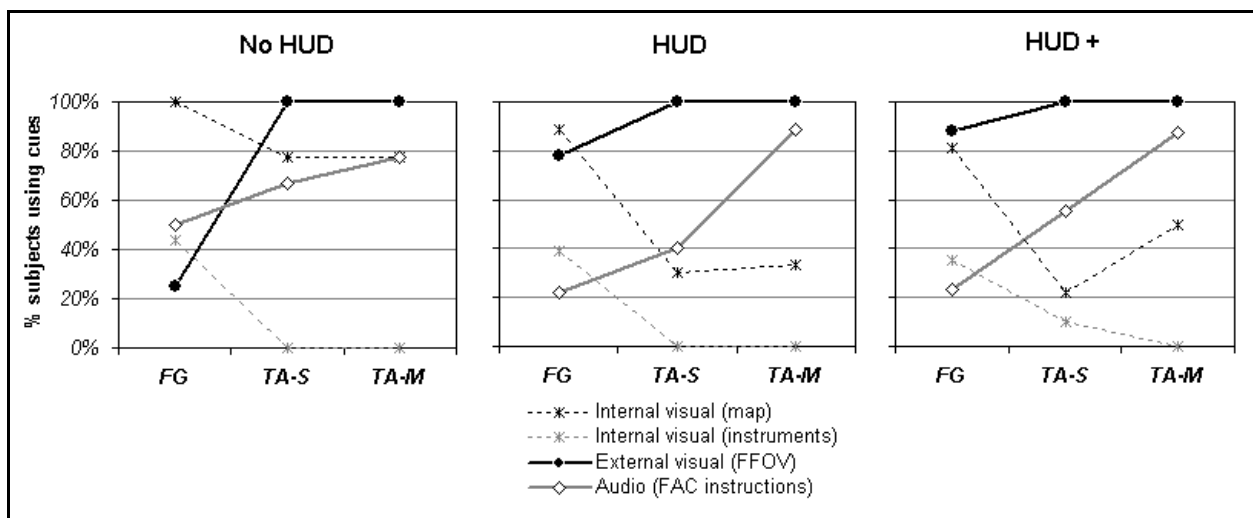


Figure 4-28. Percentage of subjects reporting the use of various cues during each phase of flight, for each of the three displays tested in Experiment C. FG = flight guidance phase, TA-S = acquisition of stationary target, TA-M = acquisition of moving target.

## 5. Conclusions

Subjects in all three experiments demonstrated that pilots must transition between primarily internal (head-down, instrument-driven) and external (head-up, out of the cockpit) guidance during air-to-ground target acquisition missions. Specifically, the subjects in these experiments relied more on the moving-map display and digital readouts of altitude, heading, and airspeed (“internal” cues) during the flight guidance phase of a mission, and they shifted their attention to focus more intently on the view outside their virtual cockpit (“external” cues) during the target acquisition phase. If the target had moved from its expected location, subjects needed to continue switching their focus between internal and external cues to correlate the various sources of information and find the target. Subjects relied more heavily on the FAC’s instructions during target acquisition than during flight guidance, and they relied most heavily on the FAC in the case of a hard-to-find target.

Experiments B and C attempted to identify cockpit display techniques and tools that could be used to help synchronize these internal and external paths of information, as well as provide cues that could be shared by cooperating troops (e.g., CAS and FAC) to facilitate communication. Experiment B contrasted the relative importance of two components of a typical plan-view moving-map display: 1) a detailed topographic map and 2) high-contrast overlays of the planned flight path (a yellow line) and the last known location of the target (a red triangle). The display that simply presented the flight path and target location, with no underlying map, resulted in comparable or better performance during both flight guidance and target acquisition, as compared with a display incorporating both the map and overlays. The map-only display resulted in the poorest performance during both mission phases. These results underscore the “less is more” philosophy: identify and present only the information required to accomplish the task at hand. In many cases, presenting too much information (such as a detailed topographic map) can degrade performance by forcing the subject to scan relatively useless information before successfully picking out salient cues. In other words, the distraction of clutter can outweigh the potential benefits of additional information in a display, especially when the display must support time-critical tasks such as target detection from a speeding fighter jet.

Experiment C focused on the relative merits of a heads-down, plan-view moving-map display vs. a HUD with scene-linked, conformal symbology to support flight guidance and target acquisition. Both displays (2D map and 3D HUD) presented high-contrast overlays of the planned flight path and the last known location of the target. The flight path overlay in the HUD consisted of yellow markers spaced  $\frac{1}{4}$  km apart, to provide a scene-linked distance cue. Flight guidance and *stationary* target acquisition performance were better with the HUD than without, as expected. Workload for these phases of flight was lower with the HUD than without, also as expected. Displaying the flight path and target location on the HUD incorporated the most important cues from the moving-map (an internal source of information) directly on the subject's FFOV (an external source), minimizing the need for the subject to switch focus between these two views and, therefore, supporting the transition between in and out.

An enhanced version of the HUD added a north-pointing arrow just above the target marker, which was expected to assist subjects in finding a target that had moved from its expected location. Results indicate that the enhanced HUD did improve target acquisition performance when the target had moved, compared with the first HUD and with no HUD, but this improvement was not statistically significant. Based on comments from several subjects, the incorporation of good distance and direction cues in the FFOV would be very helpful in finding an elusive target, but the north arrow that was designed for this experiment was not adequate. In particular, nothing in the proposed HUD helped the subject reacquire the search area if he or she missed the target on the first try. As soon as the subject had passed the target location marker, all cues were behind the aircraft and subjects often had difficulty reorienting the aircraft quickly to continue their search. One subject suggested using a series of rings radiating out from the target marker; even if the target was no longer at the marked spot, the rings would provide a distance reference that the pilot could use if the target was missed on the first attempt. Another design to consider would be a grid pattern on the ground, centered on the target marker. The FAC could instruct the CAS that the target had moved "3 squares east, 2 squares north" of its last known location.

The display techniques presented in this thesis combined the use of automated feature highlighting (e.g., of a planned flight path and a target's last known location) with human-

assisted target acquisition, in which a FAC (or other assistant) who has visually acquired both the target and the CAS aircraft can then lead the CAS pilot to the target. In other words, both FAC and CAS understand that the target marker on the display is simply a virtual reference feature that they can use to describe the target's *relative* movement and location. Relying solely on automated highlighting, in which the target itself is presumed highlighted (rather than the target's last known location), requires that some intelligence source can accurately relay a target's real-time position in precise geographic coordinates, which can then be highlighted on the pilot's display. The pilot then must confirm that the highlighted feature on the display is, in fact, the target of interest in the FFOV. This process can fail if the highlighted target is incorrect, due to poor intelligence or system failure, and the pilot does not confirm the target, due to high workload and time pressure (Conejo and Wickens, 1997). The use of semi-automated, human-assisted target highlighting should encourage the CAS pilot to maintain communication with the FAC and verify a potential target location before taking action, increasing the chances of successful target acquisition and decreasing the probability of error.

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## Appendix A. Flight Simulator to GPS (FS2GPS) Program Source Code

The fs2gps program performs the following functions:

- Extracts positional information from Microsoft Flight Simulator 2002 in real-time, using a netpipes socket utility developed by Microsoft;
- Converts the data to National Marine Electronics Association (NMEA) 0183 compliant Global Positioning Satellite (GPS) strings; and
- Ports the GPS latitude and longitude values to the FalconView moving-map program at a rate of once per second.

The software was written by Joshua Pollack (MIT Aeronautics and Astronautics Department) and Stephanie Edwards (NRL Code 7440.1, Moving-Map Capabilities Team) in support of this thesis.

---

main.cpp .....	77
FlightRecorder.h .....	88

---

```

/* main.cpp */

#include <stdio.h>
#include <string.h>
#include <windows.h>
#include <malloc.h>
#include <math.h>
#include <time.h>
#include "FlightRecorder.h"

struct prop {
    char uname[50];
    char pname[50];
};
struct loc {
    int degrees;
    double minutes;
};
int GetDataInit();
int csec=0;
int osec=0;
void GetDataClose();
void *RGetData(long);
void *SGetData(long);
void PObjectDefinition(char *, int);
void PPropertyDictionary(char *, int);
void PFrame(char *, int);
void AddProp(FRPropertyDescriptor *, char *, char *);
void AddObj(FRObjectDescriptor *, char *);
void SendGPS();
int PDataRecord();
int PDataSection();
int propmatch(int);
void fixTX(HANDLE, int);

double planedata[50];
time_t btime;
struct tm *ltime;
loc *dec2deg(double);
void WriteABuffer(char *, DWORD);
const START_RECORDING = 0x0001B001;
const STOP_RECORDING = 0x0001B002;
const START_PLAYBACK = 0x0001B003;
const STOP_PLAYBACK = 0x0001B004;
const char sFSHandleMagic[] = {'<', 'H', 'A', '>'};

```

```

char *mbuffer;
char *bbuffer;
long datainbuffer=0;
long cposinbuffer=0;
int datafromfile = 0; // 1 is file, 0 is live.
prop pdatabase[50];

FILE *stream;
HANDLE hReadPipe, hWritePipe;
HANDLE hComm;
DCB dcb={0};

int main () {

    hComm = CreateFile ("COM1", GENERIC_WRITE, 0, NULL, OPEN_EXISTING,
                        FILE_ATTRIBUTE_NORMAL, NULL);
    fixTX(hComm, 1);

    if (GetDataInit() == 0) return 0;

    FRHeader *h;

    h=(FRHeader *)RGetData(sizeof(FRHeader));

    while (PDataRecord()) { }

    free(h);

    GetDataClose();
    CloseHandle(hComm);
    return 1;
}

int PDataRecord() { //returns 0 if there are no more records.
    FRDataRecordHeader *drh;
    FRDataRecordFooter *drf;
    FRFooter *f;

    drh=(FRDataRecordHeader *)RGetData(sizeof(FRDataRecordHeader));
    while(PDataSection()) { }
    drf=(FRDataRecordFooter *)RGetData(sizeof(FRDataRecordFooter));

    //printf("\t%d %d\n",drh->size,drf->size);
    free(drh);
    free(drf);
    f=(FRFooter *)SGetData(sizeof(FRFooter));

```

```

    if (f->magic[0] == 'B') {
        free(f);
        return 1;
    }
    free(f);
    return 0;
}

int PDataSection() {
    FRDataSectionHeader *dsh;
    FRDataRecordFooter *drf;
    char *data;
    dsh=(FRDataSectionHeader *)RGetData(sizeof(FRDataSectionHeader));
    //printf("%c",dsh->magic[0]);
    data=(char *)RGetData((dsh->size)-sizeof(FRDataSectionHeader));
    switch(dsh->magic[0]) {
        case 'O':
            PObjectDefinition(data, dsh->size-sizeof(FRDataSectionHeader));
            break;
        case 'P':
            PPropertyDictionary(data, dsh->size-sizeof(FRDataSectionHeader));
            break;
        case 'F':
            PFrame(data, dsh->size-sizeof(FRDataSectionHeader));
            break;
    }

    time(&btime);
    ltime=localtime(&btime);
    osec=csec;
    csec=ltime->tm_sec;
    if (osec != csec) {
        //printf("Beep!!\n");
        SendGPS();
    }
    //SendGPS();

    free(data);
    free(dsh);

    drf=(FRDataRecordFooter *)SGetData(sizeof(FRDataRecordFooter));
    if (drf->crc == 0) {
        free(drf);
        return 0;
    }
}

```



```

    }
    free(drf);
    return 1;

}
// the bulk
void PObjectDefinition(char *data, int size) {
    FRObjectDescriptor *od=(FRObjectDescriptor *)malloc(sizeof(FRObjectDescriptor));
    char *objectname;
    long offset=0;

    while (offset<size) {
        memcpy(od,data+offset,sizeof(FRObjectDescriptor));
        offset+=sizeof(FRObjectDescriptor);
        objectname=(char *)malloc(sizeof(char)*od->length+1);
        memcpy(objectname,data+offset,sizeof(char)*od->length);
        offset+=sizeof(char)*od->length;
        objectname[od->length]='\0';
        AddObj(od,objectname);
        free(objectname);
    }
    free(od);
}

void PPropertyDictionary(char *data, int size) {
    FRPropertyDescriptor *pd=(FRPropertyDescriptor
*)malloc(sizeof(FRPropertyDescriptor));
    char *propertyname;
    char *unitsname;

    long offset=0;
    while (offset<size) {
        memcpy(pd,data+offset,sizeof(FRPropertyDescriptor));
        offset+=sizeof(FRPropertyDescriptor);

        propertyname=(char *)malloc(sizeof(char)*pd->namesize+1);
        unitsname=(char *)malloc(sizeof(char)*pd->unitsize+1);

        memcpy(propertyname,data+offset,pd->namesize*sizeof(char));
        offset+=sizeof(char)*pd->namesize;
        memcpy(unitsname,data+offset,pd->unitsize*sizeof(char));
        offset+=sizeof(char)*pd->unitsize;

        propertyname[pd->namesize]='\0';
        unitsname[pd->unitsize]='\0';
    }
}

```

```

        AddProp(pd, propertyname, unitsname);
        free(propertyname);
        free(unitsname);
    }
    free(pd);

}

void PFrame(char *data, int size) {
    FRFrameTime *ft=(FRFrameTime *)malloc(sizeof(FRFrameTime));
    FRPropertyValue *pv=(FRPropertyValue *)malloc(sizeof(FRPropertyValue));

    unsigned short tbool;
    long tlong=0;
    double tdouble=0;
    char *tstring;
    long offset = 0;

    //printf("size is %d\n",size);
    //return;
    memcpy(ft,data+offset,sizeof(FRFrameTime));
    offset+=sizeof(FRFrameTime);

    while (offset<size) {
        memcpy(pv,data+offset,sizeof(FRPropertyValue));
        offset+=sizeof(FRPropertyValue);
        //if (propmatch(pv->PropertyId))
        //    printf("%s ",pdatabase[pv->PropertyId].pname);

        switch (pv->ValueType) {
            case 1:
                memcpy(&tbool,data+offset,sizeof(unsigned short));
                offset+=sizeof(unsigned short);
                //    if (propmatch(pv->PropertyId))
                //        printf("%u ",tbool);
                break;
            case 2:
                memcpy(&tdouble,data+offset,sizeof(double));
                offset+=8;
                //if (propmatch(pv->PropertyId))
                //printf("%f ",tdouble);
                if (pv->PropertyId<42)
                    planedata[pv->PropertyId]=tdouble;
                break;
            case 3:

```

```

        memcpy(&tlong,data+offset,sizeof(long));
        offset+=sizeof(long);
//      if (propmatch(pv->PropertyId))
//      printf("%ld ",tlong);
        break;
    case 4:
        memcpy(&tlong,data+offset,sizeof(long));
        offset+=sizeof(long);
        tstring=(char *)malloc(sizeof(char)*tlong);
        memcpy(tstring,data+offset,sizeof(char)*tlong);
        offset+=sizeof(char)*tlong;
//      if (propmatch(pv->PropertyId))
//      printf("%s ",tstring);
        free(tstring);
        break;

    }
    //if (propmatch(pv->PropertyId))
    //      printf("%s\n",pdatabase[pv->PropertyId].uname);

}
free(pv);
free(ft);
}

void AddProp(FRPropertyDescriptor *pd, char *propertyname, char *unitsname) {
    //printf("%s ",propertyname);
    //printf("%d ",pd->PropertyID);
    //printf("%s\n",unitsname);
    memcpy(&pdatabase[pd->PropertyID].pname,propertyname,pd->namesize+1);
    memcpy(&pdatabase[pd->PropertyID].uname,unitsname,pd->unitsize+1);
}

void AddObj(FRObjectDescriptor *ob, char *objectname){
    //printf("\t%s\n",objectname);

}
// data manip.

int GetDataInit() {
    if (datafromfile) {
        stream=fopen("fsdata","r+b");
    } else {

```

```

mbuffer=(char *)calloc(4096,sizeof(char));
bbuffer=(char *)calloc(4096,sizeof(char));

char MagicName[sizeof (sFSHandleMagic)+8+8+1];
COPYDATASTRUCT cpdata;
HWND hWnd;

// create pipe.
printf("Creating pipe...");
CreatePipe (&hReadPipe, &hWritePipe, NULL, 4096);
memcpy (MagicName, sFSHandleMagic, sizeof (sFSHandleMagic));
wsprintf (MagicName + sizeof (sFSHandleMagic), "%08.8X%08.8X",
(DWORD)hWritePipe, GetCurrentProcessId ());
printf("done!\n");

// find flight sim.
printf("Finding Flight Sim window...");
hWnd = FindWindow ("FS98MAIN", NULL);
if (!hWnd) {
    printf("\n\tFlightsim is not running.\n");
    return 0;
}
printf("done!\n");

// tell it to start recording.
printf("Telling Flight Sim to start recording...");
cpdata.dwData = START_RECORDING;
cpdata.lpData = const_cast<char*>(MagicName);
cpdata.cbData = strlen ((char *)MagicName) + 1;
SendMessage (hWnd, WM_COPYDATA, (WPARAM)hWnd, (LPARAM)&cpdata);
printf("done!\n");

}
return 1;
}

void GetDataClose() {
    fclose(stream);
}

void *RGetData(long bytes){ // returns a pointer to bytes number of bytes
    char *rarray = (char *)calloc(bytes,sizeof(char));
    if (datafromfile) {
        //read the data into rarray
        fread(rarray,sizeof(char),bytes,stream);
    } else {

```

```

        if (datainbuffer-cposinbuffer<bytes){
            unsigned long dataread=0;
            if ((bytes+cposinbuffer)>4096) {
                memcpy(bbuffer,mbuffer+cposinbuffer,datainbuffer-cposinbuffer);
                free(mbuffer);
                mbuffer=(char *)calloc(4096,sizeof(char));
                memcpy(mbuffer,bbuffer,datainbuffer-cposinbuffer);
                datainbuffer=datainbuffer-cposinbuffer;
                cposinbuffer=0;
            }
            while (datainbuffer-cposinbuffer<bytes) {
                ReadFile(hReadPipe,mbuffer+datainbuffer,bytes-(datainbuffer-
cposinbuffer),&dataread,NULL);
                datainbuffer+=dataread;
            }
        }
        memcpy(rarray,mbuffer+cposinbuffer,bytes);
        cposinbuffer+=bytes;
    }
    return rarray;
}

```

```

void *SGetData(long bytes){ // returns a pointer to bytes number of bytes
                                // and resets the file position!
    char *rarray = (char *)calloc(bytes,sizeof(char));
    if (datafromfile) {
        fpos_t pos;
        fgetpos(stream,&pos);
        fread(rarray,sizeof(char),bytes,stream);
        fsetpos(stream,&pos);
    } else {
        if (datainbuffer-cposinbuffer<bytes){
            unsigned long dataread=0;
            if ((bytes+cposinbuffer)>4096) {
                memcpy(bbuffer,mbuffer+cposinbuffer,datainbuffer-cposinbuffer);
                free(mbuffer);
                mbuffer=(char *)calloc(4096,sizeof(char));
                memcpy(mbuffer,bbuffer,datainbuffer-cposinbuffer);
                datainbuffer=datainbuffer-cposinbuffer;
                cposinbuffer=0;
            }
            while (datainbuffer-cposinbuffer<bytes) {
                ReadFile(hReadPipe,mbuffer+datainbuffer,bytes-(datainbuffer-
cposinbuffer),&dataread,NULL);
                datainbuffer+=dataread;
            }
        }
    }
}

```

```

        }
        memcpy(rarray,mbuffer+cposinbuffer,bytes);
    }
    return rarray;
}

int propmatch (int pid) {
    if (pid==3)
        return 1;

    return 0;
}

void SendGPS (){
double
latitude,longitude,altitude,heading_true,heading_magnetic,airspeed,abstime,airspeed_kmh;
loc *latloc, *longloc;
char latc = 'N';
char longc = 'E';
char buff[2][4096];
DWORD buffsize[3];
//DWORD buffwritten[3];

ltime=localtime(&btime);

latitude=planedata[1];
longitude=planedata[2];
altitude=planedata[3];
heading_true=planedata[6];
airspeed=planedata[12];
heading_magnetic=planedata[13];
abstime=planedata[40];
airspeed_kmh=airspeed*0.539956803455724;
if ((latitude == 0 )|| (longitude == 0 )|| (altitude == 0) || (heading_true == 0) || (heading_magnetic
== 0) || (airspeed == 0))
return;

if (latitude<0) latc='S';
if (longitude<0) longc='W';
latitude=fabs(latitude);
longitude=fabs(longitude);
latloc=dec2deg(latitude);
longloc=dec2deg(longitude);

```

```

buffsize[0]=sprintf(buff[0],"$GPGLL,%02d%06.3f,%c,%03d%06.3f,%c,%02d%02d%02d.00,A\
n\r",latloc->degrees,latloc->minutes,latc,longloc->degrees,longloc->minutes,longc,ltime-
>tm_hour,ltime->tm_min,ltime->tm_sec);
//buffsize[0]=sprintf(buff[0],"$GPGGA,%02d%02d%02d.00,%02d%06.3f,%c,%03d%06.3f,%c,
1,08,,%.1f,M,,,\n\r",ltime->tm_hour,ltime->tm_min,ltime->tm_sec,latloc->degrees,latloc-
>minutes,latc,longloc->degrees,longloc->minutes,longc,altitude);
buffsize[1]=sprintf(buff[1],"$GPVTG,%.2f,T,%.2f,M,%.2f,N,%.2f,K\n\r",heading_true,heading
_magnetic,airspeed,airspeed_kmh);

```

```

WriteABuffer(buff[0],buffsize[0]);
WriteABuffer(buff[1],buffsize[1]);

```

```

printf("%s\n%s\n",buff[0],buff[1]);

```

```

free(latloc);
free(longloc);
}

```

```

void WriteABuffer(char * lpBuf, DWORD dwToWrite)
{
    DWORD dwWritten;

    PurgeComm(hComm, PURGE_TXCLEAR);
    WriteFile(hComm, lpBuf, dwToWrite, &dwWritten, NULL);
}

```

```

loc *dec2deg(double dec) {
    loc *loc1=(loc *)malloc(sizeof(loc));
    loc1->degrees=(int)floor(dec);
    dec-=floor(dec);
    dec*=60;
    loc1->minutes=dec;

    return loc1;
}

```

```

void fixTX(HANDLE port, int com)
{
    DCB dcb;
    COMMTIMEOUTS CommTimeOuts;

    GetCommTimeouts (port, &CommTimeOuts);
    CommTimeOuts.ReadIntervalTimeout = MAXDWORD;
    CommTimeOuts.ReadTotalTimeoutMultiplier = 0;
    CommTimeOuts.ReadTotalTimeoutConstant = 1000;
}

```

```

CommTimeOuts.WriteTotalTimeoutMultiplier = 0;
CommTimeOuts.WriteTotalTimeoutConstant = 1000;
if ( !SetCommTimeouts( port, &CommTimeOuts ))
    CloseHandle(port);

    GetCommState (port, &dcb);

    dcb.DCBlength = sizeof(DCB);
// Change the DCB structure settings.
    dcb.BaudRate = 4800;           // Current baud
    dcb.fBinary = TRUE;           // Binary mode; no EOF check
    dcb.fParity = TRUE;           // Enable parity checking
    dcb.fOutxCtsFlow = FALSE;     // No CTS output flow control
    dcb.fOutxDsrFlow = FALSE;     // No DSR output flow control
    dcb.fDtrControl = DTR_CONTROL_ENABLE;
                                // DTR flow control type
    dcb.fDsrSensitivity = FALSE;  // DSR sensitivity
    dcb.fTXContinueOnXoff = TRUE; // XOFF continues Tx
    dcb.fOutX = FALSE;           // No XON/XOFF out flow control
    dcb.fInX = FALSE;            // No XON/XOFF in flow control
    dcb.fErrorChar = FALSE;      // Disable error replacement
    dcb.fNull = FALSE;           // Disable null stripping
    dcb.fRtsControl = RTS_CONTROL_ENABLE;
                                // RTS flow control
    dcb.fAbortOnError = FALSE;    // Do not abort reads/writes on
                                // error
    dcb.ByteSize = 8;             // Number of bits/byte, 4-8
    dcb.Parity = NOPARITY;        // 0-4=no,odd,even,mark,space
    dcb.StopBits = ONESTOPBIT;    // 0,1,2 = 1, 1.5, 2

    SetCommState(port, &dcb);

    PurgeComm(port, PURGE_TXCLEAR);
}

```



```

/* FlightRecorder.h */

/* This file defines the format of flights to be recorded and played back by FlightSim
 * 2002. These recorded flights are also known as .FSR files.
 * Copyright Microsoft Corp, 2001
 */

/* Recorded flight file starts with the file header.
 */
struct FRHeader {
    char magic[4];
    // must be 'F' 'S' 'T' 'B'
    char lsb[2];
    // must be 8, 0
    WORD version;
    // must be 0x800
};

/* Recorded flight file ends with the tail record, with 3 parts. The 1st and 3rd parts are
 * identical. They identify the record as the tail record and give the size of the record.
 */
struct FRFooter {
    char magic[4];
    // must be 'T' 'A' 'T' 'B'
    DWORD size;
    // total size of Footer record
};

/* The second part of the Footer record, the one between FRFooter structs is a sequence of
Footer items
 * There can be any number of trailer items, including no items at all
 */

/* Each of the Footer item consists from the item header and item data.
 * First goes the header, than, if length field is of the header is not zero, the data.
 * The number of bytes occupied by the extra data is rounded up to dividable by 4 number.
 */
struct FRFooterHeader {
    WORD type;
    // either FRFooterTitleItem or FRFooterDescriptionItem; see bellow
    WORD length;
    // exact size of extra data for this item
};

enum {
    FRFooterTitleItem = 1, // flight title

```

```

        FRFooterDescriptionItem = 2                                // flight description
    };

/* The rest of a recorded flight file, between the file header and the Footer record are data
Records.
* Each data Record has the Record header, any number of sections and the Record footer
*/
struct FRDataRecordHeader {
    char magic[4];
    // must be 'B' 'F' 'T' 'B'
    DWORD size;
    // total size of this data Record including the header and the footer
};
struct FRDataRecordFooter {
    DWORD crc;
    // must be 0
    DWORD size;
    // total size of this data Record including the header and the footer
};

/* Section start with the section header
*/
struct FRDataSectionHeader {
    char magic[4];
    // defines what section is this
    DWORD size;
    // total size (including the header) of the section in bytes
};

/* Object dictionary section defines object recorded in this file. The user aircraft is one of those
objects
* The magic for this section is 'O' 'D' 'T' 'B'.
* The section consists from the header and one or more object descriptors.
* Object Descriptor is FRObjDescriptor struct and object name.
*/
struct FRObjDescriptor {
    WORD code;
    // struct id in the upper 4 bits; 0 in the lower

    // each struct of objects has to have an uniq id

    // ((struct_id) << 12) | 0
    WORD length;
    // string length of the name of the struct object

```

```

        // the name itself immediately follows this struct
};

/* Object name recognizable by FS2002 are:
 *   UserAircraft          - object representing the user aircraft
 *   Enviroment            - object which has such properties as local time and
time zone
 */

/* Property dictionary section defines which properties have object form the object dictionary
 * The magic for this section is 'P' 'D' 'T' 'B'.
 * The section consists from the header and one or more property descriptors.
 * Property Descriptor is FRPropertyDescriptor struct which followed by the property name and
units in which this property is expressed
 */

struct FRPropertyDescriptor {
    WORD ObjectID;
    // struct id of the property's object in the upper 4 bits; 0 in the lower
    WORD PropertyID;
    // uniq id by which this property will be referenced further in the file
    WORD type;
    // either this property is number, string or else; see below
    WORD namesize;
    // length of the name; the name itself goes immediately after this struct
    WORD unitsize;
    // length if the units name; the units name goes after the property name
};

enum {
    FRBooleanProperty = 1,                // occupies 2
bytes; takes 0 for no, 1 for yes
    FRNumberProperty = 2,                //
occupies 8 bytes; any number stored in 'double' format
    FROrdinalProperty = 3,                // occupies 4
bytes; signed integer number
    FRStringProperty = 4,                // occupies 4
bytes for string length plus bytes for actual string
};

/* Properties name for the aircraft and enviroment objects are the same names as used by XML
gauges.
 * They defined in "properties" document from the Panel SDK.
 * That document also defines possible unit names, such as "feet" or "knots".

```

```

*/

/* Frame section defines the state of different object at the moment.
* The magic for this section is 'F' 'R' 'T' 'B'
* Section header is followed by time information
*/

struct FRFrameTime {
    LONGLONG TimeStamp;
        // number of 1/256th of seconds since some moment in history
    DWORD FrameNumber;
        // a sequential number of this frame in this file
    DWORD Ticks;
        // an internal FlightSim counter; increases its value even when

        // FlightSim is paused or minimized
};

/* Current values of object properties are recorded by data elements
* struct FRPropertyValue serves as the name tag of each element
*/
struct FRPropertyValue {
    WORD ObjectId;
        // which object does this property belong to?

        // struct id in the upper 4 bits, instance number in the lower 12 bits
    WORD PropertyId;
        // property id; taken from Property Dictionary
    WORD ValueType;
        // one of FR???Property enums; see above
};

/* The data value follows
* The number of bytes taken by the value depends on "ValueType" field and described above
*/

/* It is possible to invoke FlightSim recording capabilities programmatically from another
program without end user interaction
* Here, described an outline how to do this
*
* First, program needs to find the main FlightSim window using FindWindow WIN32 API
function
*/
#define FLIGHTSIM_MAIN_WINDOW_struct "FS98MAIN"

```

```

/* Second, fill in COPYDATASTRUCT (WIN32 API struct) as follow
*   set dwData field to one of the following values
*/
#define FLIGHTSIM_RECORD_START_VIDEO_RECORDING 0x1B001
#define FLIGHTSIM_RECORD_STOP_VIDEO_RECORDING 0x1B002
#define FLIGHTSIM_RECORD_START_VIDEO_PLAYBACK 0x1B003
#define FLIGHTSIM_RECORD_STOP_VIDEO_PLAYBACK 0x1B004
/*   set lpData to point to filename string
*   set cbData to filename string length (add 1 for trailing zero)
*/
/* Third program invokes SendMessage function with WM_COPYDATA as the second
argument
*   SendMessage (hFilghSimMainWnd, WM_COPYDATA,
(WPARAM)hFilghSimMainWnd, (LPARAM)cpdsFlightSimRecordCOPYDATASTRUCT);
*/

/* If a program needs to have an immediate access to recorded data, it can create a data pipe,
using CreatePipe WIN32 API,
* and create a special filename with encoded data pipe handle using this kind of technique
*   wsprintf (szfileName,
FLIGHTSIM_RECORD_ENCODED_HANDLE_FILENAME, (int) hPipeHandle, (int)
GetCurrentProcessId ());
*/
#define FLIGHTSIM_RECORD_ENCODED_HANDLE_FILENAME "<HA>%08.8X%08.8X"

```

## **Appendix B. RMSE Calculations of Flight Path, Altitude, and Airspeed Deviations**

---

Flight Guidance Performance: RMSE (path) .....	94
Deviation in Altitude: RMSE (altitude).....	95
Deviation in Airspeed: RMSE (airspeed) .....	96

---

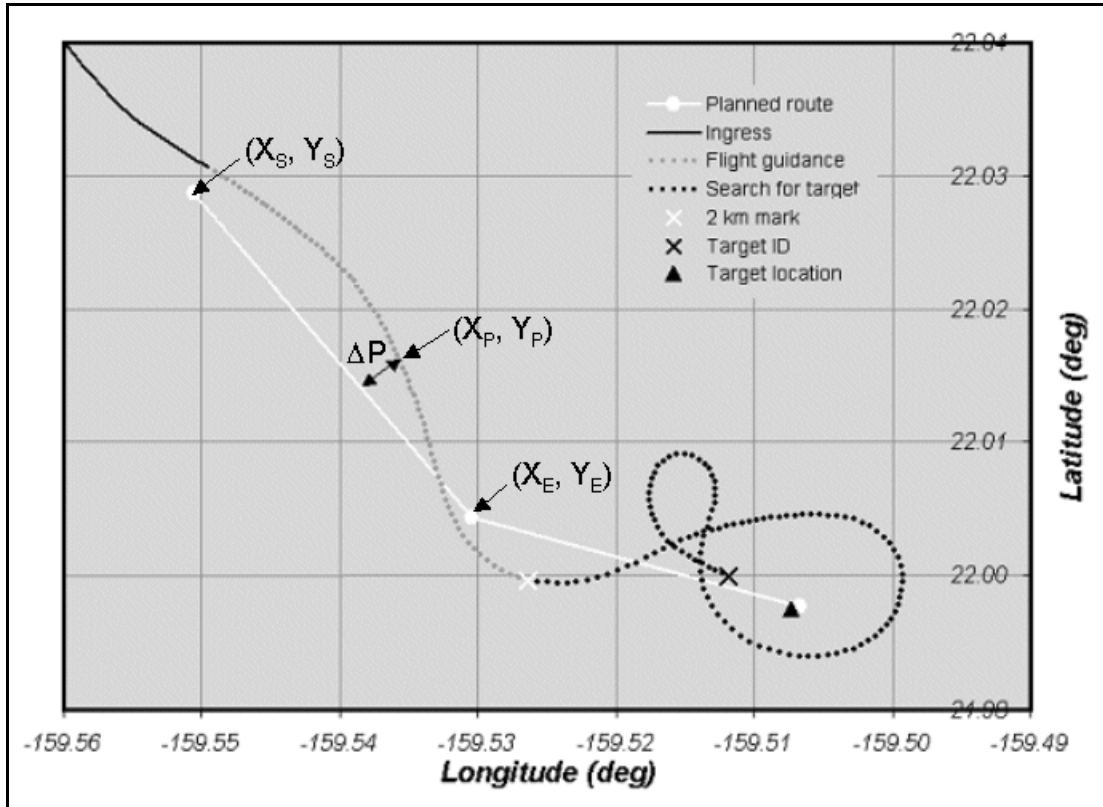
### Flight Guidance Performance: RMSE (path)

Flight guidance performance is represented by the root mean square error (RMSE) between the planned flight path and the actual aircraft track. This value is referred to as RMSE (path) and is calculated as follows:

$$\text{RMSE (path)} = \text{SQRT} [\Sigma(\Delta P^2) / n]$$

$$\Delta P = \frac{C_X C_Y [(Y_E - Y_S)(X_P - X_S) - (X_E - X_S)(Y_P - Y_S)]}{\text{SQRT} [(C_X(X_E - X_S))^2 + (C_Y(Y_E - Y_S))^2]}$$

where  $(X_P, Y_P)$  = longitude (X) and latitude (Y) of point P along the actual flight path,  
 $(X_S, Y_S)$  = longitude and latitude of the starting point of the planned route segment,  
 $(X_E, Y_E)$  = longitude and latitude of the ending point of the planned route segment,  
 $C_X$  = constant to convert longitude into meters (for the average latitude of the course),  
 $C_Y$  = constant to convert latitude into meters (which is independent of longitude).  
 $n$  = number of points recorded along actual flight path (1 point per second of flight time).



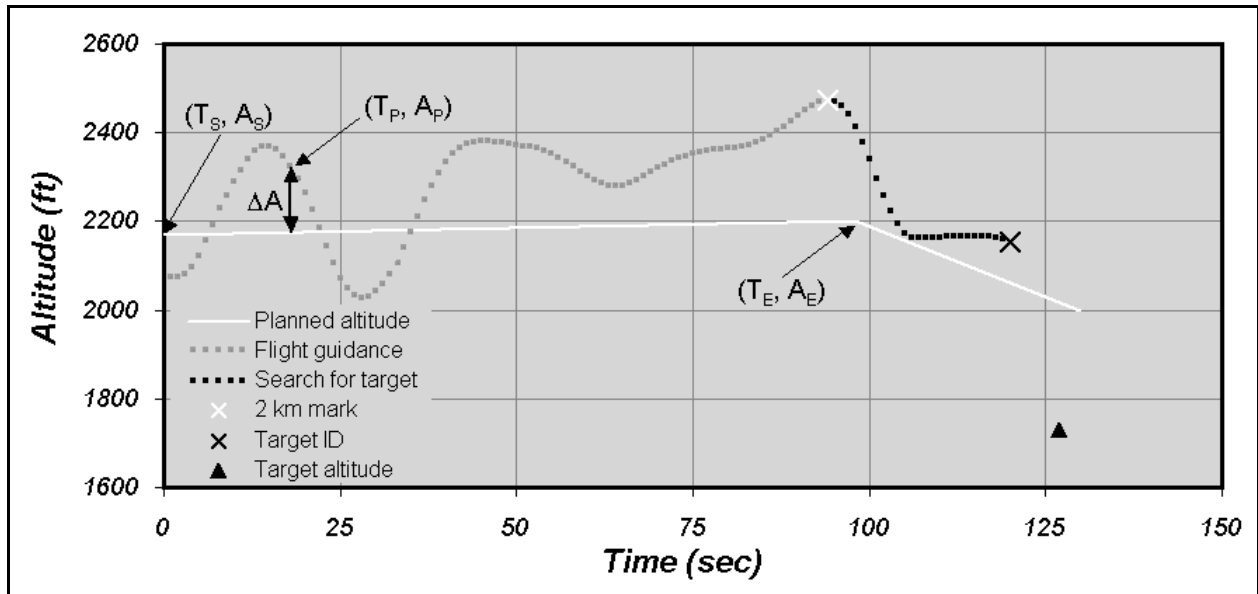
### Deviation in altitude: RMSE (altitude)

Deviation in altitude was calculated as the RMSE between planned and actual altitude along the flight path, as follows:

$$\text{RMSE (altitude)} = \text{SQRT} [\sum(\Delta A^2) / n]$$

$$\Delta A = A_P - \left[ A_S + \frac{(A_E - A_S)(T_P - T_S)}{(T_E - T_S)} \right]$$

where  $A_P$  = altitude (ft) of point  $P$  along the actual flight path,  
 $A_S$  = altitude of the starting point of the planned route segment,  
 $A_E$  = altitude of the ending point of the planned route segment,  
 $T_P$  = time (min) when point  $P$  was recorded in the FS2002 log file,  
 $T_S$  = time the route segment started (when the plane should have been at altitude  $A_S$ )  
 $T_E$  = time the route segment ended (when the plane should have been at altitude  $A_E$ )  
 $n$  = number of points recorded along actual flight path (1 point per second of flight time).





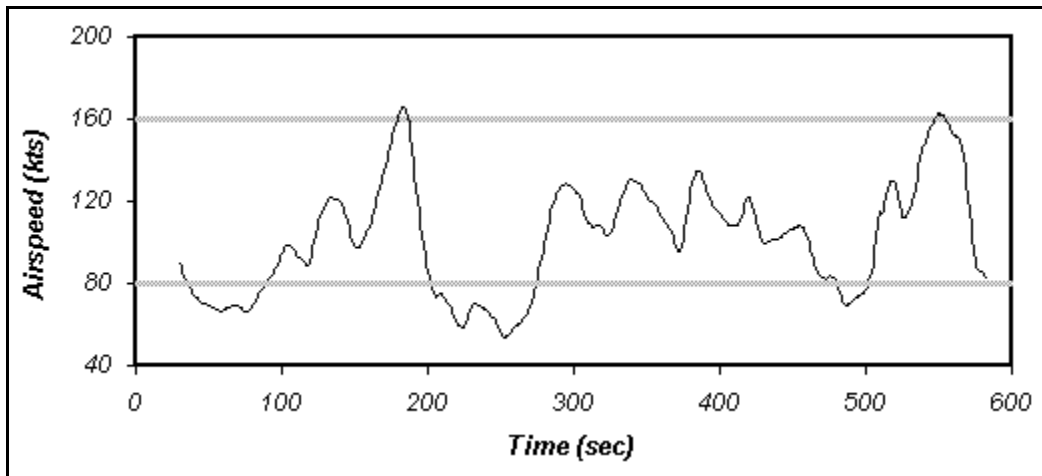
### Deviation in airspeed: RMSE (airspeed)

Deviation in airspeed was calculated as the RMSE between the outer limits of the allowed airspeed (80 – 160 kts) and actual airspeed, as follows:

$$\text{RMSE (airspeed)} = \text{SQRT} [\sum(\Delta S^2) / n]$$

$$\Delta S = \begin{cases} 80 - S_p & \text{if } S_p < 80 \\ S_p - 160 & \text{if } S_p > 160 \\ 0 & \text{otherwise} \end{cases}$$

where  $S_p$  = airspeed (kts) at point P during the flight.



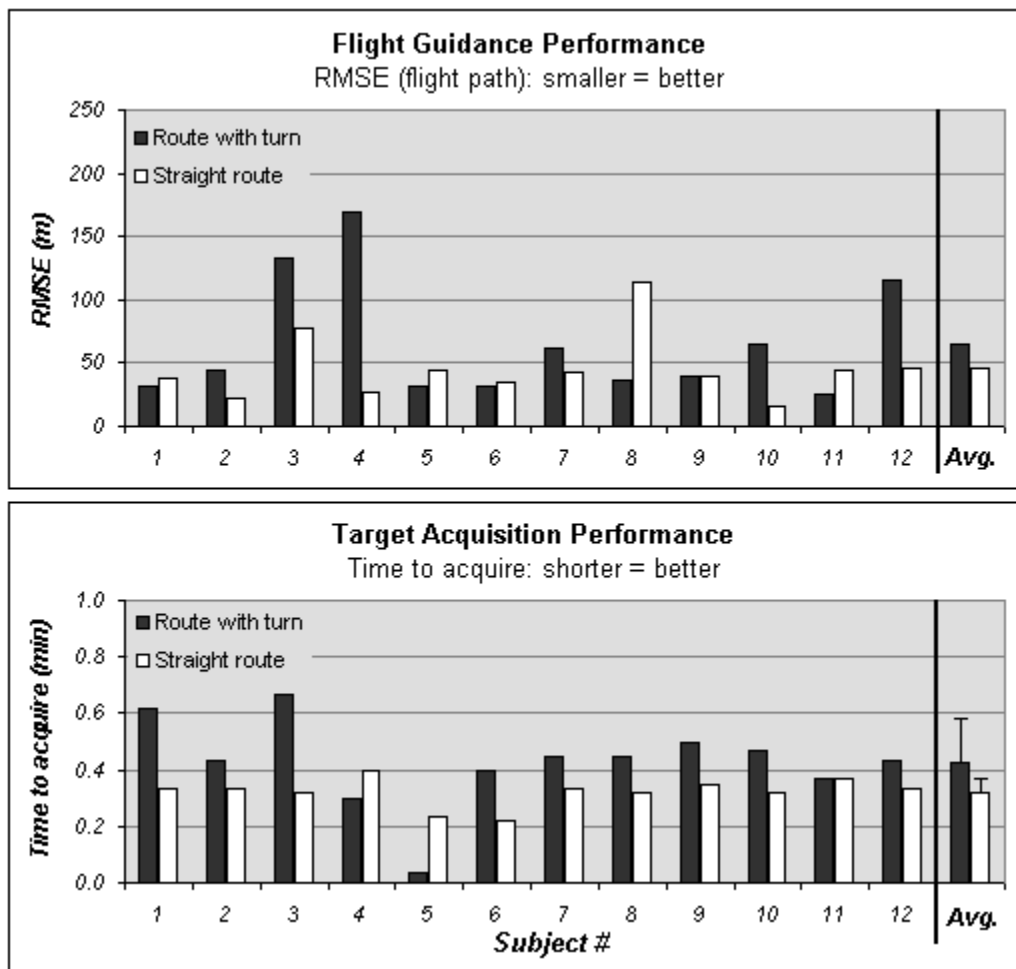
**Appendix C. Experimental Results by Subject**

---

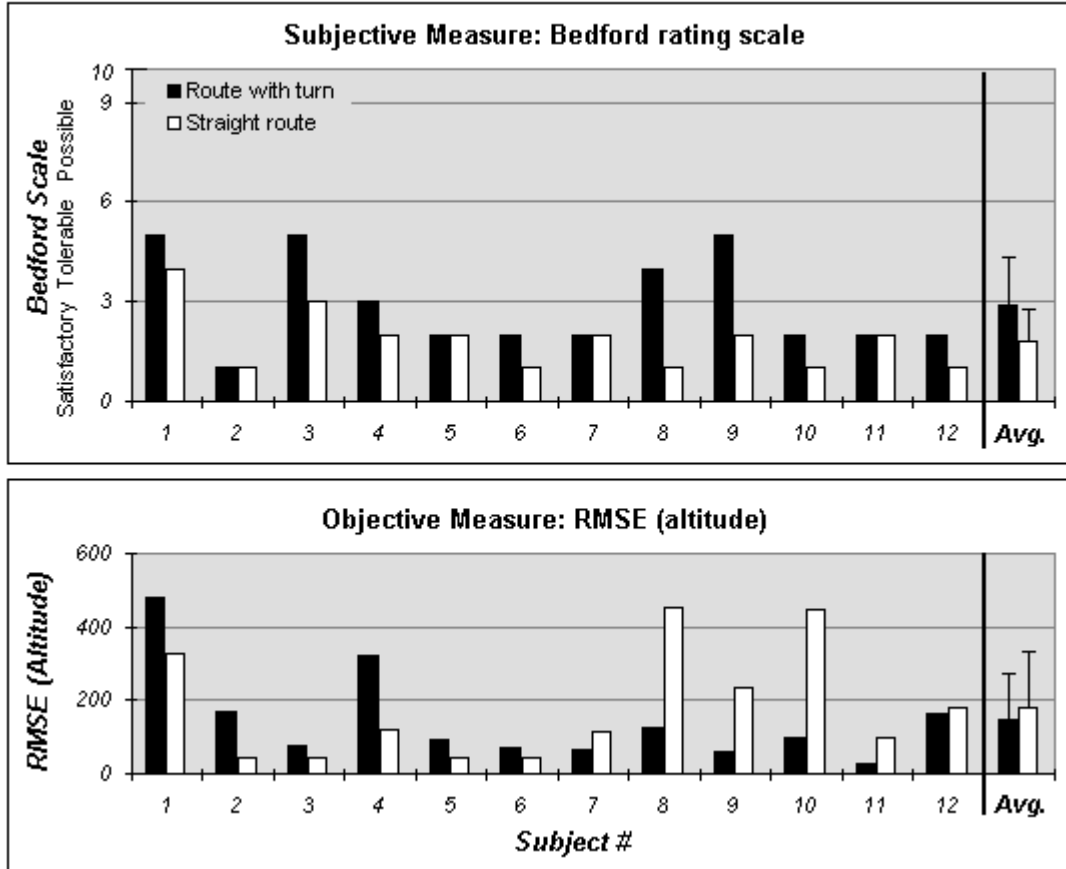
Experiment A .....	98
Experiment B .....	101
Experiment C .....	104

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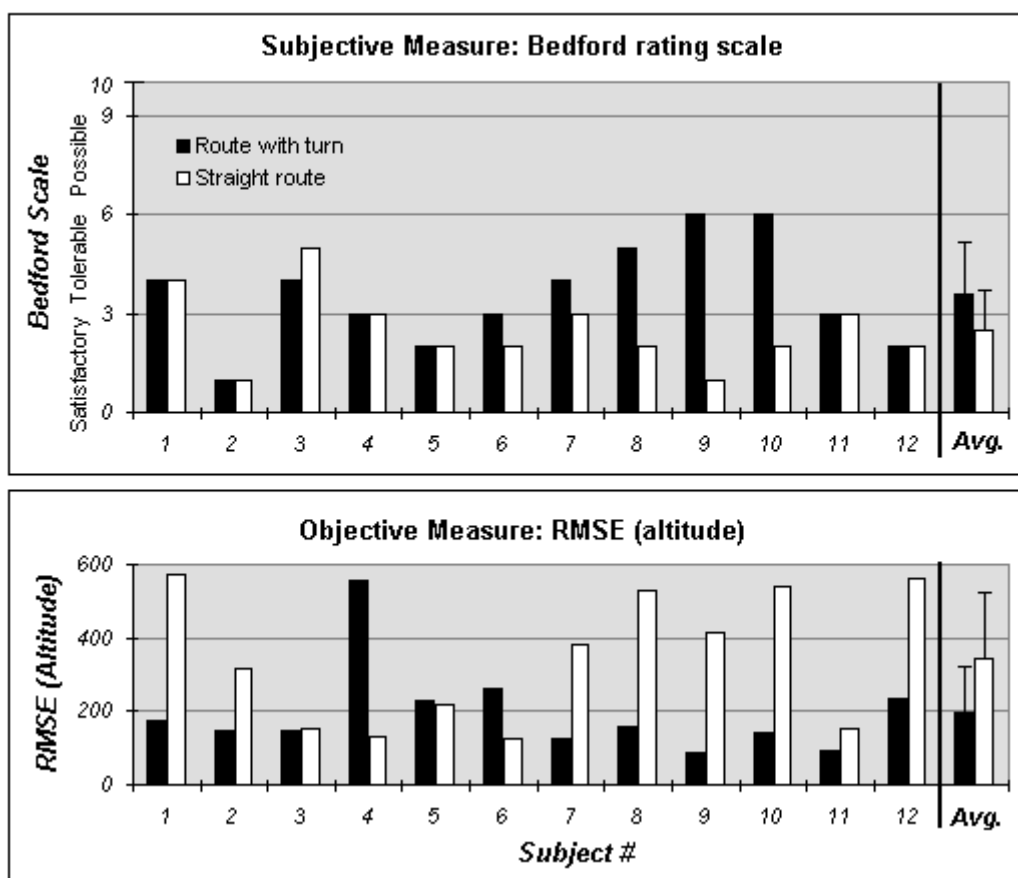
## Experiment A: Performance and Workload Summary, by Subject



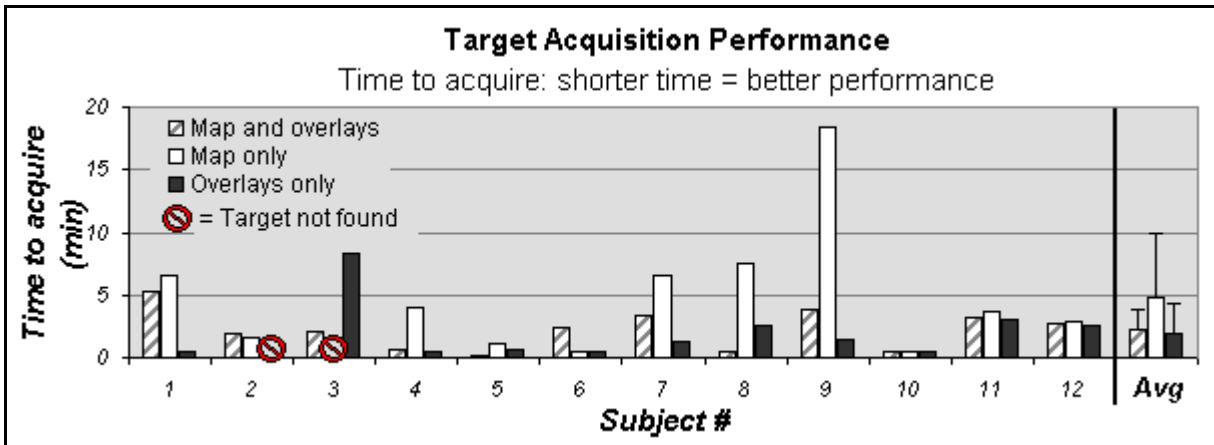
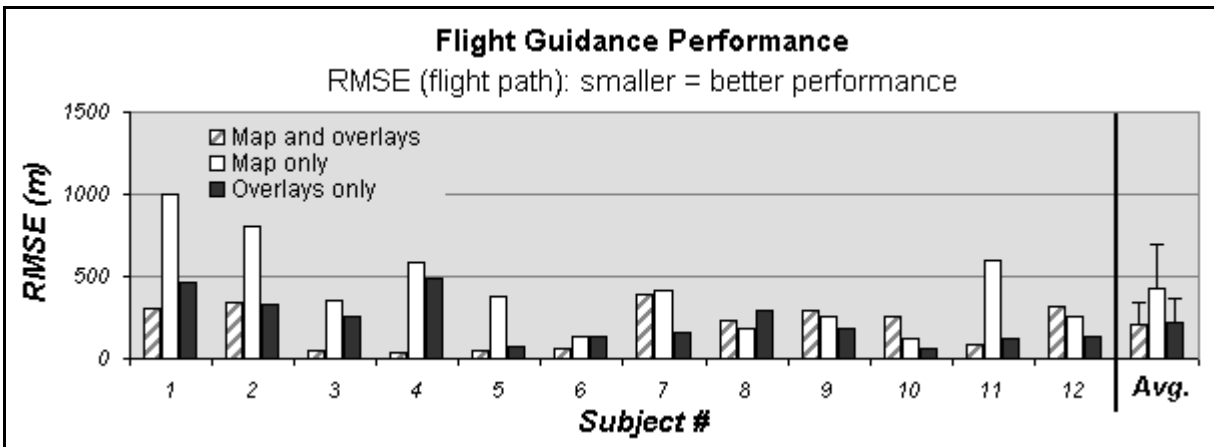
## Flight Guidance Workload (lower values = less work)



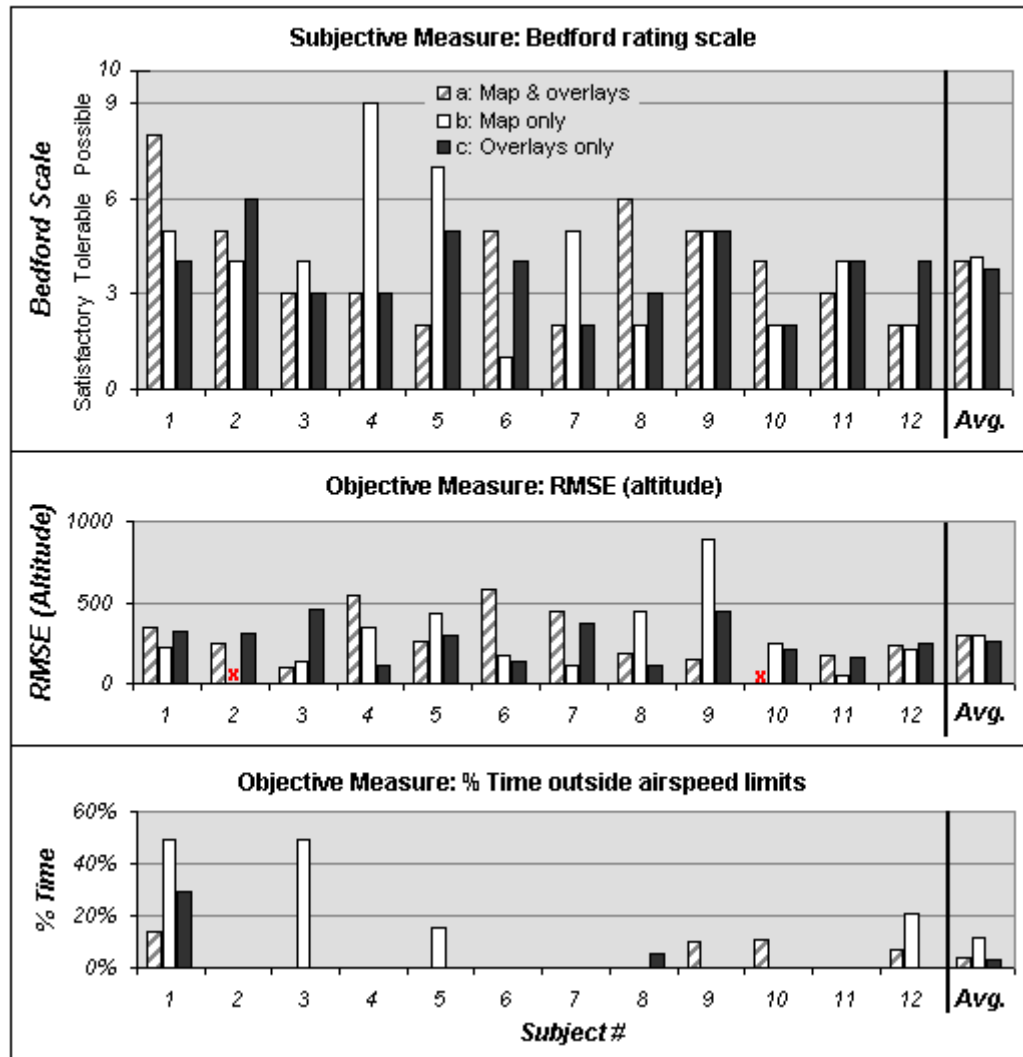
# Target Acquisition Workload (lower values = less work)



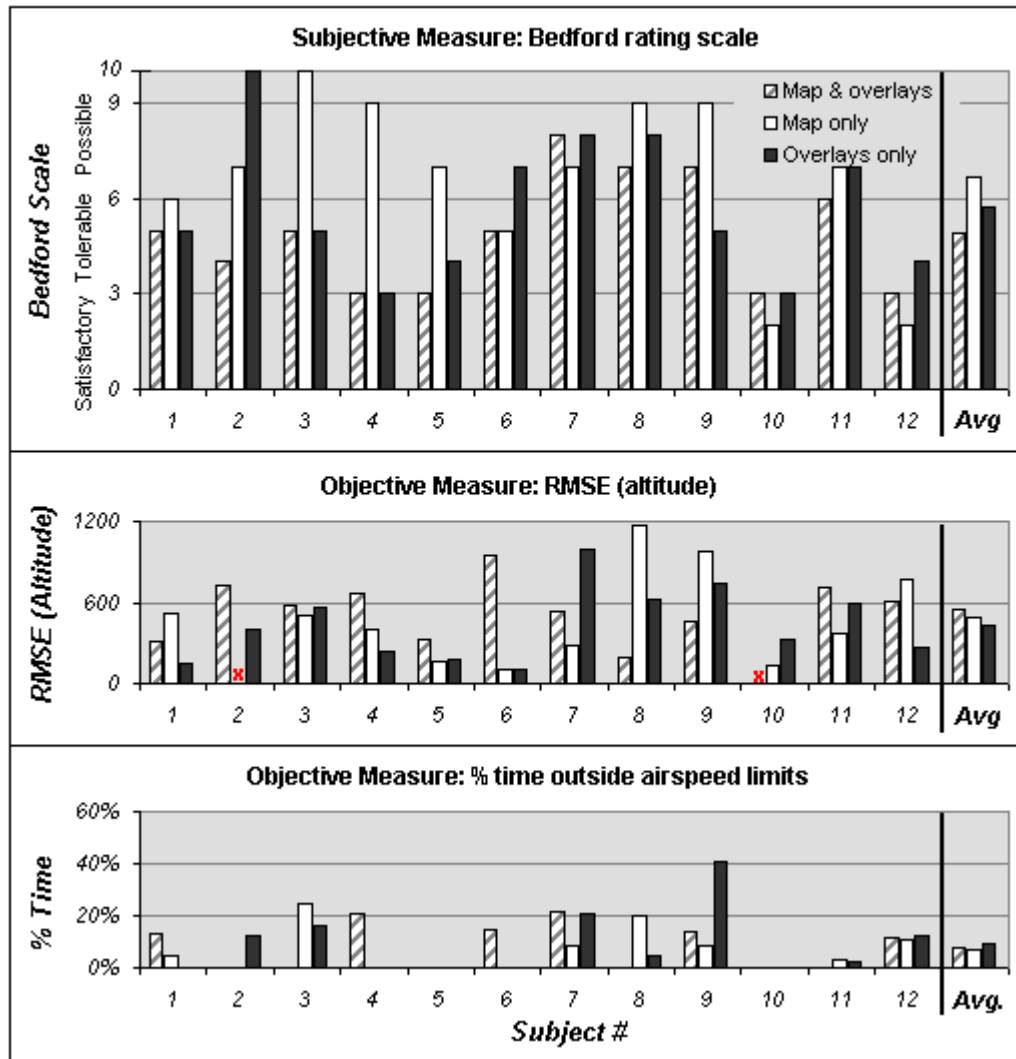
## Experiment B: Performance and Workload Summary, by Subject



## Flight Guidance Workload (lower values = less work)

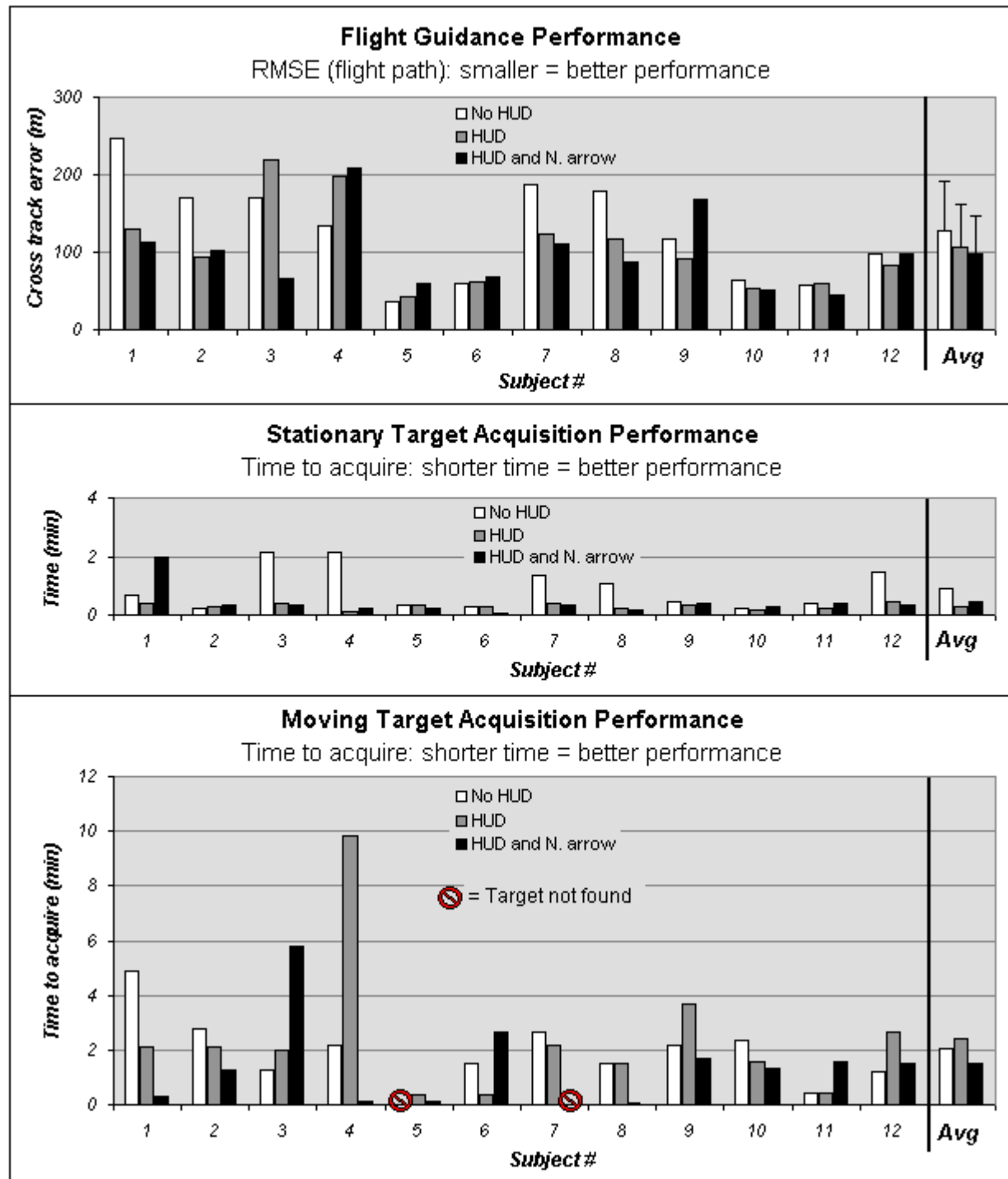


# Target Acquisition Workload (lower values = less work)

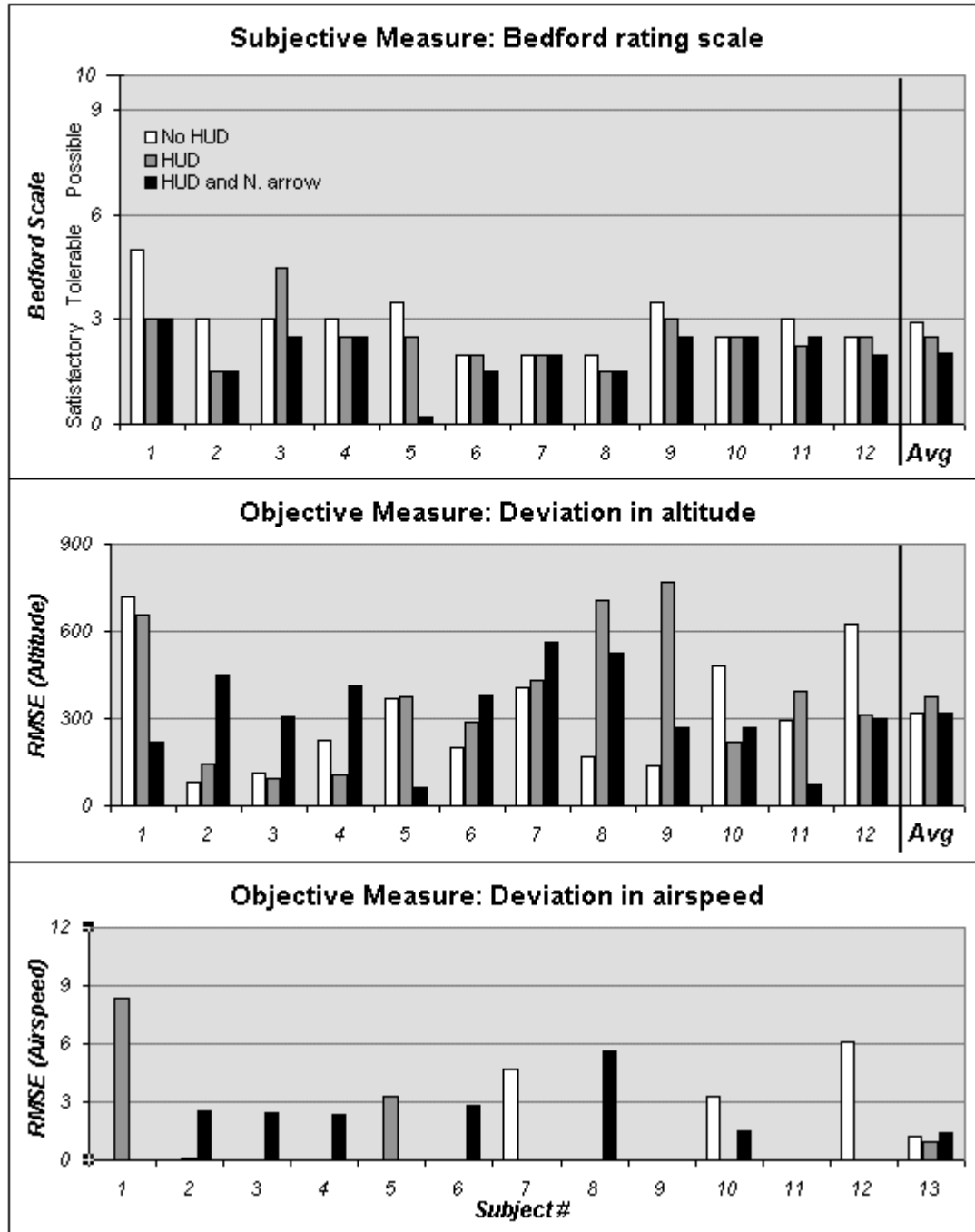




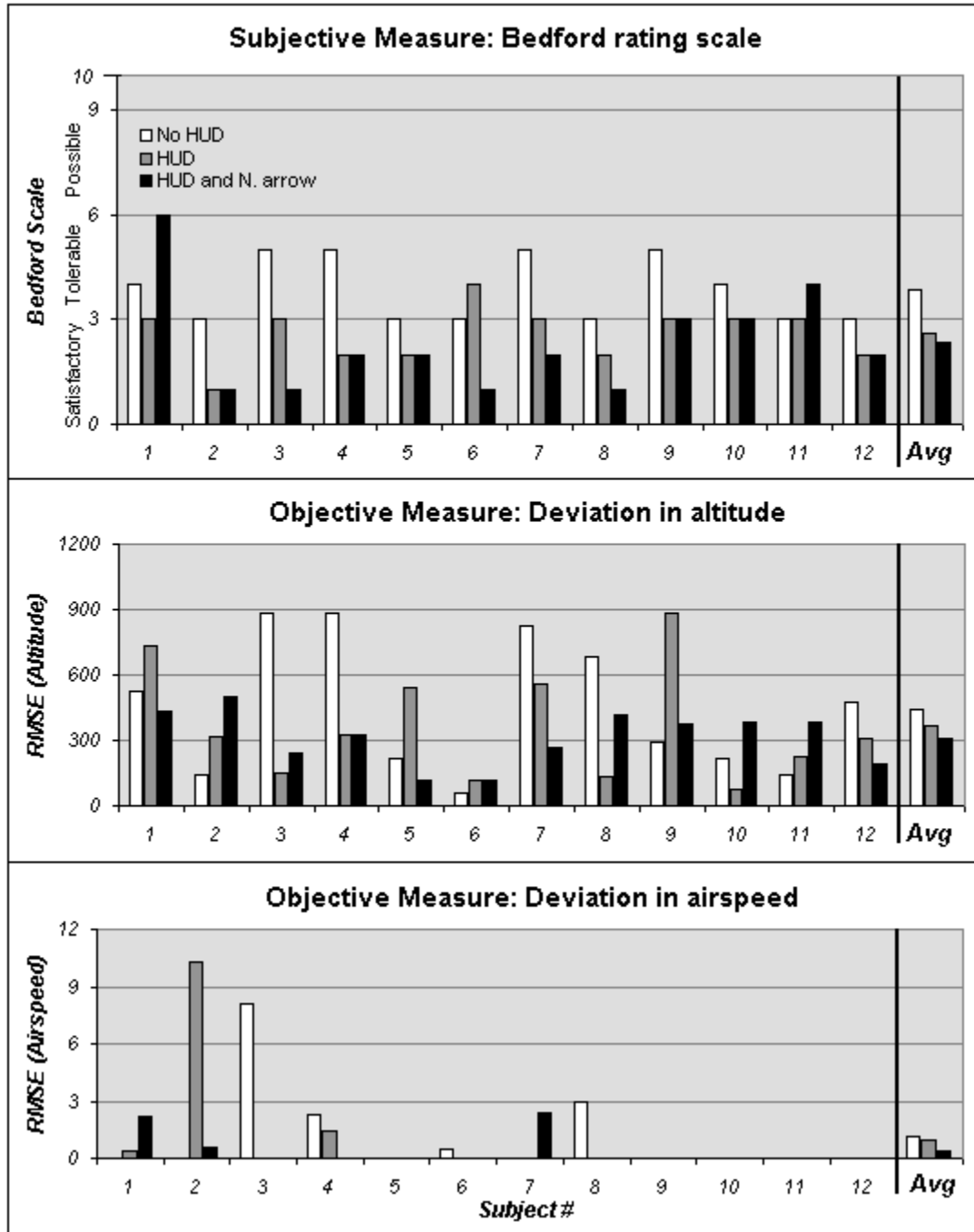
## Experiment C: Performance and Workload Summary, by Subject



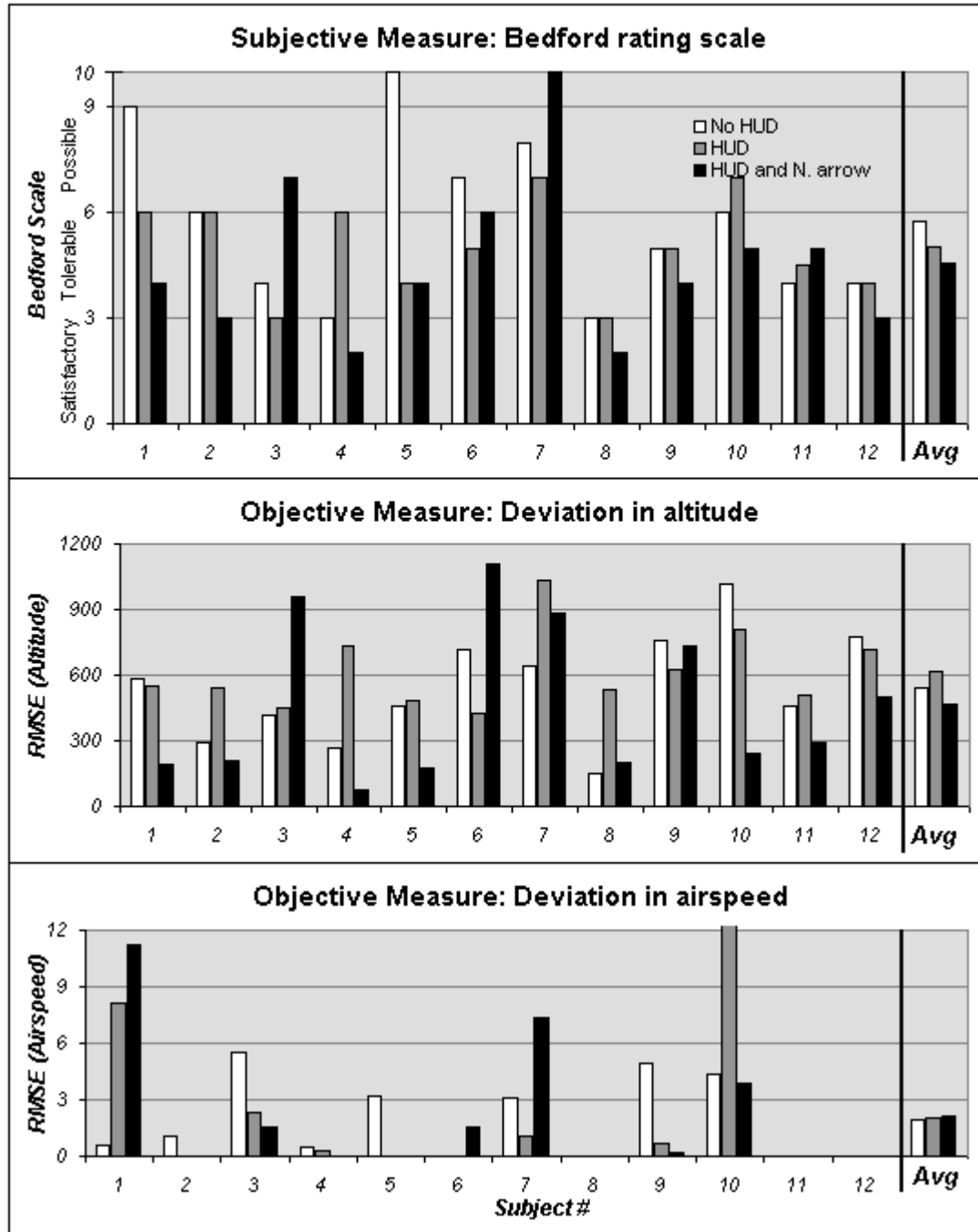
# Flight Guidance Workload (lower values = less work)



# Stationary Target Acquisition Workload (lower values = less work)



# Moving Target Acquisition Workload (lower values = less work)



## Appendix D. NRL Documentation for Experiments on Human Subjects

The experimental research conducted on human subjects for this thesis was approved by the NRL Human Subjects Internal Review Board (HS-IRB# 74-001-03). The following documents were provided to all subjects who participated in the flight simulator experiments.

---

Consent form (a copy of which was signed by each subject).....109

Debriefing statement.....112

---

## CONSENT FORM

**HS-IRB Number:** 74-001-03

**Title of study:** Cognitive Issues Related to Advanced Cockpit Displays:  
Supporting the Transition between Internal and External Guidance

**Authority:** This research is conducted under authority delegated from the Secretary of the Navy to the Naval Research Laboratory. Governing regulations 32 CFR § 219, SECNAVINST 3900.39C, DODD 3216.2, and NRLINST 3900.2A require that the researchers obtain your written, voluntary consent before you may participate in the study, experiment, or test. You are not required to complete this form, and you are not required to provide the requested information. However, if you decide not to complete the form or not to provide the requested information, the researchers cannot allow you to participate in the research study.

**Purpose of study:** Three research experiments are planned to better understand what types of visual cues in a moving-map display or heads-up display can best assist a military pilot during air-to-ground targeting missions. In particular, the researcher is interested in determining which cues would best help a pilot 1) navigate to a given target area (the “flight guidance” phase of the mission) and 2) search for, find and identify a target (the “target acquisition” phase).

**Procedures:** For each experiment, you will be seated about 2 ft away from two laptop computers. One laptop will run Microsoft Flight Simulator 2002; the other will run a moving-map display. A Microsoft Sidewinder Precision 2 joystick will allow you to control pitch, roll, and throttle while flying a virtual aircraft using the flight simulator. The simulator settings will be as follows:

- Aircraft type: Cessna 172 Skyhawk
- Display viewpoint: out front cockpit window
- Scenery: Waimea Canyon in Kauai, Hawaii
- Weather: summer afternoon, few clouds, no precipitation, unlimited visibility, no winds
- Instruments: simple digital readout of latitude, longitude, altitude, heading, and airspeed at the top of the display, and analog compass at the top-right corner.

Prior to the start of the experiments, you will fly a training mission consisting of six flight legs. You can fly this mission as often as you like before starting the experiments. When you are ready, you will fly 11 missions to complete three experiments: 2 missions for Experiment A, followed by 3 missions for Experiment B, and finally 6 missions for Experiment C. The only differences that you will notice among Experiments A, B, and C will be the amount of information presented to you on the flight simulator scene and the moving-map display.

There will be two main phases of each mission: flight guidance and target acquisition. Each mission starts with your aircraft already in flight and at a safe altitude and attitude. During flight guidance, your primary goal will be to stay on a preset flight path. The target acquisition phase will start when the experimenter gives you instructions to find a target (which will be a tank, jeep, or fuel truck), at which point your primary goal will be to find and identify the target as

quickly as possible. During both phases, you will also be told to ascend or descend to a certain altitude and maintain a specified airspeed.

You will be debriefed after each mission. For each phase of the mission, you will be asked to gauge your workload, on a scale from 1 (easiest) to 10 (hardest), based on a modified Bedford Workload Scale (Roscoe and Ellis, 1990). Any additional comments that you care to provide will be recorded as well.

**Expected duration of participation:** The training mission is expected to take approximately 10 minutes. You can repeat the training mission as often as you would like. The experimental missions will take a maximum of approximately 10 minutes each, depending on the length of time required to find each target. If you cannot find the target in a reasonable amount of time, you can choose to end the mission, and the experimenter will note that the target could not be found. If any given target cannot be found after 20 minutes, the experimenter will end the mission and note that the target could not be found. There will be a 2-4 minute break between each mission while the experimenter sets up the next mission. Therefore, the maximum estimated experimental time is 154 minutes (2.5 hours), as summarized in the following table:

	<b>Experiment A</b>	<b>Experiment B</b>	<b>Experiment C</b>
# Missions:	2	3	6
Est. maximum time / mission:	10	10	10
Est. maximum time for breaks:	8	12	24
Est. max. time / experiment:	28	42	84
<b>Total est. time (excluding training):</b>		<b>154 min</b>	

**Risks to subject:** There are no significant risks associated with running the flight simulator, although some people might experience eye, back or neck strain, headache, or dizziness during or after the tests. If you feel any discomfort, you may take a break or stop the experiment at any time. You may also arrange the laptops, joystick, and chair to be most comfortable for you.

**Benefits:** You will not be financially compensated for your participation in these experiments, but your participation in this research is expected to benefit military aviators and, potentially, commercial pilots. A critical issue in military aviation is the pilot's ability to transition between primarily internal (i.e., head-down, instrument-driven) and external (i.e., head-up, out of the cockpit) guidance. Military pilots report difficulties during this transition, particularly during time-critical target acquisition missions. Parallel issues exist in civilian aviation; for example, during circling Instrument Flight Rules (IFR) approaches, the pilot must transition between internal guidance while flying through clouds and external guidance below the ceiling. Tools to synchronize internal and external information paths are expected to support communication and coordination among mission subjects (e.g., military pilots and ground troops; or civilian pilots and air traffic controllers), increasing the potential for mission success.

**Use and confidentiality of data:** The data collected will be analyzed and results will be published. The data and all related information will be held in confidence and will not be associated with your name or identity outside the context of the study or in any published results.

The data and related information will remain confidential even after the study has ended. The data and documents will be stored at the Naval Research Laboratory Code 7440, Stennis Space Center, MS. The primary document resulting from this research will also be stored in the form of a Master of Science thesis in the Aeronautics and Astronautics Department of the Massachusetts Institute of Technology, Cambridge, MA.

**Voluntary participation:** You can choose whether or not to participate in this study. If you volunteer to be in this study, you may withdraw at any time without consequences of any kind.

**Point of contact:** For questions about this research, please contact Maura C. Lohrenz, 228-688-4611, [mlohrenz@nrlssc.navy.mil](mailto:mlohrenz@nrlssc.navy.mil). For questions about the ethical aspects of this study, your rights as a volunteer, or any problem related to the protection of study volunteers, contact the Chair of NRL's Human Subjects Institutional Review Board, Lt. Joseph Cohn, at 202-404-8624.

**You will be given a copy of this form for your records.**

**Statement of consent:**

I have read the above information. I have had the opportunity to ask questions, and they have been answered. I understand that I do not have to fill out this form and that I do not have to participate in this research. I voluntarily consent to participate in the research.

---

Signature of Volunteer Date

---

Signature of Investigator Date



## DEBRIEFING STATEMENT

### **Title of Experiment**

Cognitive Issues Related to Advanced Cockpit Displays: Supporting the Transition between Internal and External Guidance

**Name of Experimenter:** Maura Lohrenz, NRL Code 7440.1  
[mlohrenz@nrlssc.navy.mil](mailto:mlohrenz@nrlssc.navy.mil)  
228-688-4611

### **Purpose of Experiment**

Three experiments are planned to better understand what types of visual cues in a moving-map display or heads-up display (HUD) can best assist a military pilot during air-to-ground missions such as Close Air Support (CAS) and Forward Air Control (FAC). In particular, the experimenter is interested in determining which cues would best help the CAS pilot 1) navigate to a given target area (the “flight guidance” phase of the mission) and 2) search for, find and identify a target (the “target acquisition” phase). The hypothesis is that in cases in which the target is stationary and in a known location, the most important cues will be those that support the pilot’s guidance to the target area. If the target has moved, the pilot will still need flight guidance cues, but he or she also will need target acquisition cues, which must be shared between the CAS pilot and a ground-based FAC to facilitate communication between the crewmembers about the new target location.

### **Potential Benefits**

A critical issue in military aviation is the pilot’s ability to transition between primarily internal (i.e., head-down, instrument-driven) and external (i.e., head-up, out of the cockpit) guidance. Military pilots report difficulties during this transition phase, particularly during time-critical target acquisition missions such as CAS and FAC. Parallel issues exist in civilian aviation; for example, during circling Instrument Flight Rules (IFR) approaches, the pilot must transition between internal guidance while flying through clouds and external guidance below the ceiling. The military scenario is complicated by the fact that the target may be mobile and unpredictable, whereas the civilian “target” – the runway – is fixed. The goal of this thesis is to investigate, design, and test advanced cockpit display techniques to improve this transition phase between internal and external guidance. Tools to synchronize internal and external information paths are expected to support communication and coordination among mission subjects (e.g., CAS pilots and FAC ground troops; or civilian pilots and air traffic controllers), improving the transition phase and increasing the potential for mission success.

Note: results of this work will be included in my masters’ thesis, to be submitted to the Department of Aeronautics and Astronautics at the Massachusetts Institute of Technology.